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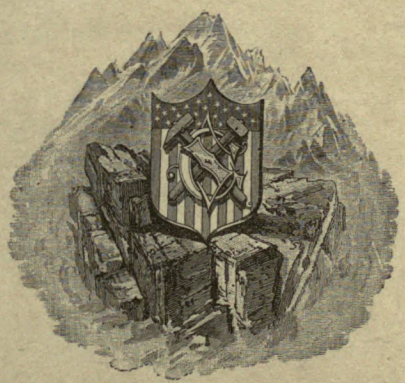
A

TREATISE ON METAMORPHISM

BY

CHARLES RICHARD VAN HISE



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CONTENTS.

	Page.
LETTER OF TRANSMITTAL	29
CHAPTER I.—INTRODUCTION	31
General nature of alterations	31
Classification of metamorphism	39
Geological factors affecting the alterations of rocks	40
Composition	40
Structures and textures	40
Porosity	40
Water and gaseous content	41
Climatic and geographic conditions	41
Time	41
Environment	42
Degree of movement	42
Depth	43
CHAPTER II.—THE FORCES OF METAMORPHISM	45
Chemical energy	45
Gravity	46
Mechanical action	46
Molecular mechanical action	47
Mass mechanical action	49
Permanent strain without openings	49
Permanent strain with openings	49
Permanent strain with closing of openings and welding	50
Water action	50
Heat and light	51
Sources of heat and light	51
The sun as a source of heat and light	51
Heat derived from within the earth by conduction or convection through water or magma	53
Mechanical action as a source of heat	54
Chemical action as a source of heat	54
Effects of heat and light on alterations of rocks	54
Direct effects of heat and light	55
Mechanical effects	55
Chemical effects	56
Indirect effects of heat and light	56
General statements	57

Page.

CHAPTER III.—THE AGENTS OF METAMORPHISM 58
General statement 58
Part I. Gaseous solutions 59
Section 1. Chemical and physical principles controlling the action of gases 60
Gases present 60
The pressure 61
The temperature 61
Section 2. Geological work of gases 62
Part II. Aqueous solutions and solids 63
General considerations 63
Section 1. Chemical and physical principles controlling the action of ground water 65
Principles of solutions applicable to ground water 65
Solution of gases in ground waters 68
Gases present 68
The pressure 70
The temperature 72
Solids in solution 72
Solution of solids in ground water 72
Compounds present 76
Relations of solution and pressure 77
Relations of solution and temperature 79
Speed of solution 79
Quantity of material which may be held in solution 79
Relations of solution to absorption and liberation of heat 81
Diffusion 82
Principles of chemical reactions applicable to ground waters 84
General statement 84
Definitions 84
Dissociation 84
Hydrolysis 86
Reactions 87
Equilibrium 90
Homogeneous and heterogeneous systems 90
Nature and speed of reactions 91
The compounds 91
Strength of the solutions 94
Mechanical action 95
Speed of chemical action 95
Direct deformation effect 95
Strain without rupture 95
Strain with rupture 98
Readjustment of particles 98
Indirect heat effect 99
Nature of the chemical reactions 100

CHAPTER III.—THE AGENTS OF METAMORPHISM—Continued. Page.
Part II. Aqueous solutions and solids—Continued.
Section 1. Chemical and physical principles, etc.—Continued.
Principles of chemical reactions applicable to ground waters—Continued.
Nature and speed of reactions—Continued.
Mechanical action—Continued.
Nature of the chemical reactions—Continued.
Smaller rock volume as the result of solution and deposition without change in chemical composition 101
Recrystallization and condensation without change of minerals 101
Recrystallization and condensation with change of minerals. 102
Smaller volume as the result of solution and redeposition with change in chemical composition 103
Crystallization and condensation of amorphous compounds. 103
Recrystallization and condensation of crystallized compounds 103
General statements 104
Heat 105
Relations of chemical action, mechanical action, and heat 110
Precipitation 113
Precipitation by change of pressure 114
Precipitation by change of temperature 115
Precipitation by reactions between aqueous solutions 116
Precipitation by reactions between aqueous solutions and gases 119
Precipitation by reactions between solutions and solids 120
Section 2. Circulation and work of ground water 123
Universal presence of water in rocks 123
Pore space of rocks 125
Circulation of ground water 129
Openings in rocks 129
Form and continuity of openings 129
Size of openings 134
Supercapillary openings 137
Capillary openings 138
Subcapillary openings 143
Percentage of openings, or pore space 146
Forces producing water circulation 146
Gravity 146
Heat 147
Gravity and heat 148
Mechanical action 149
Molecular attraction 150
Vegetation 152
General statements 152

CHAPTER III.—THE AGENTS OF METAMORPHISM—Continued. Page.
Part II. Aqueous solutions and solids—Continued.
Section 2. Circulation and work of ground water—Continued.
Circulation of ground water—Continued.
The factor opposing water circulation 153
General statements 154
Geological work of ground water 156
CHAPTER IV.—THE ZONES AND BELTS OF METAMORPHISM 159
General considerations 159
Zone of katamorphism 160
Belt of weathering 163
Belt of cementation 164
Belts of weathering and cementation contrasted 166
Zone of anamorphism 167
Relations of zones of katamorphism and anamorphism 170
General considerations 186
Relations of zones of katamorphism and anamorphism to zones of fracture and flowage 187
Upper limit of zone of flowage 187
CHAPTER V.—MINERALS 192
Section 1. Chemical and mineral composition of the known crust of the earth 192
Section 2. General nature of alterations 202
Alteration without change in chemical composition 202
Molecular rearrangement 202
Simple recrystallization 202
Alteration with change in chemical composition 202
Alteration without addition or subtraction of material 203
Alteration with addition or subtraction of material 203
General statements 206
Section 3. Rock-making minerals 207
Manner of treatment 207
General statements 207
Native elements 212
Graphite 212
Occurrence 212
Alterations 212
The sulphides 212
Pyrrhotite, pyrite, and marcasite 213
Occurrence 213
Alterations 214
The fluorides 216
Fluorite 216
Occurrence 216
Alterations 216
The oxides 217
Quartz 217
Occurrence 217

CHAPTER V.—MINERALS—Continued. Page.
Section 3. Rock-making minerals—Continued.
The oxides—Continued.
Quartz—Continued.
Modifications 218
Tridymite 220
Occurrence 220
Modifications 220
Opal 221
Occurrence 221
Modifications 221
Chert, chalcedony, etc 222
Hematite group 223
Corundum, hematite, and ilmenite 223
Corundum 223
Occurrence 223
Alterations 223
Hematite 225
Occurrence 225
Alterations 226
Ilmenite 227
Occurrence 227
Alterations 227
Spinel group 228
Spinel, magnetite, and chromite 228
Spinel 228
Occurrence 228
Alterations 228
Magnetite 229
Occurrence 229
Alterations 229
Chromite 229
Occurrence 229
Alterations 230
Rutile group 230
Rutile, octahedrite, and brookite 230
Occurrence 230
Alterations 230
Diaspore group 231
Diaspore and limonite 231
Diaspore 232
Occurrence 232
Alterations 232
Limonite 232
Occurrence 232
Alterations 233

CHAPTER V.—MINERALS—Continued. Page.
Section 3. Rock-making minerals—Continued.
The oxides—Continued.
Brucite group ... 234
Brucite and gibbsite ... 234
Brucite ... 235
Occurrence ... 235
Alterations ... 235
Gibbsite ... 235
Occurrence ... 235
Alterations ... 235
The carbonates ... 236
Calcite group ... 237
Calcite, dolomite, ankerite, parankerite, magnesite, and siderite ... 237
Calcite ... 237
Occurrence ... 237
Alterations ... 238
Dolomite ... 240
Occurrence ... 240
Alterations ... 241
Ankerite and parankerite ... 242
Occurrence ... 242
Alterations ... 242
Magnesite ... 243
Occurrence ... 243
Alterations ... 243
Siderite ... 244
Occurrence ... 244
Alterations ... 244
Aragonite group ... 245
Aragonite ... 245
Occurrence ... 245
Alterations ... 245
The silicates ... 246
Glass ... 246
Occurrence ... 247
Evidence that devitrification takes place ... 247
Scale of devitrification ... 247
Rate of devitrification ... 248
Devitrification in the two zones ... 249
Minerals produced ... 251
Heat and volume relations ... 251
Feldspar group ... 252
Monoclinic or pseudomonoclinic ... 253
Orthoclase, microcline, and anorthoclase ... 253
Orthoclase and microcline ... 253

CHAPTER V.—MINERALS—Continued. Page.
Section 3. Rock-making minerals—Continued.
The silicates—Continued.
Feldspar group—Continued.
Monoclinic or pseudomonoclinic—Continued.
Orthoclase, microcline, and anorthoclase—Continued.
Orthoclase and microcline—Continued.
Occurrence 253
Alterations 253
Anorthoclase 257
Occurrence 257
Alterations 258
Triclinic 259
Albite, oligoclase, andesine, labradorite, bytownite, and anorthite 259
Occurrence 259
Alterations 260
Leucite group 266
Leucite 266
Occurrence 266
Alterations 266
Pyroxene group 267
Orthorhombic pyroxenes 267
Enstatite, bronzite, and hypersthene 267
Occurrence 268
Alterations 268
Monoclinic pyroxenes 271
Diopside, sahlite, hedenbergite, augite, acmite, spodumene, wollastonite, and pectolite 271
Occurrence 272
Alterations of the diopside-augite series 273
Alterations of pyroxenes other than the diopside-augite series 280
Amphibole group 281
Orthorhombic amphiboles 281
Anthophyllite and gedrite 281
Occurrence 281
Alterations 282
Monoclinic amphiboles 283
Tremolite, actinolite, cummingtonite, grünerite, hornblende, glaucophane, riebeckite, and arfvedsonite 283
Occurrence 283
Alterations 285
Iolite (cordierite) 291
Occurrence 291
Alterations 291
Nephelite group 292
Nephelite and cancrinite 292

CHAPTER V.—MINERALS—Continued. Page.
Section 3. Rock-making minerals—Continued.
The silicates—Continued.
Nephelite group—Continued.
Nephelite and cancrinite—Continued.
Nephelite 292
Occurrence 292
Alterations 292
Cancrinite 294
Occurrence 294
Alterations 294
Sodalite group 295
Sodalite, haüynite, and noselite 295
Sodalite 295
Occurrence 295
Alterations 295
Haüynite and noselite 297
Occurrence 297
Alterations 298
Garnet group 299
Grossularite, pyrope, almandite, spessartite, melanite, and uvarovite 299
Occurrence 300
Alterations 302
Chrysolite group 308
Forsterite, olivine, and fayalite 308
Occurrence 308
Alterations 308
Scapolite group 311
Meionite, wernerite, and marialite 311
Occurrence 312
Alterations 312
Melilite 314
Occurrence 314
Alterations 314
Gehlenite 314
Occurrence 314
Alterations 314
Vesuvianite 315
Occurrence 315
Alterations 315
Zircon group 315
Occurrence 315
Alterations 315
Aluminum-silicate group 316
Topaz, andalusite, sillimanite, and cyanite 316
Occurrence 316
Alterations 318

CHAPTER V.—MINERALS—Continued. Page.
Section 3. Rock-making minerals—Continued.
The silicates—Continued.
Epidote group 320
Zoisite, epidote, piedmontite, and allanite 320
Occurrence 320
Alterations 322
Axinite 323
Occurrence 323
Alterations 324
Prehnite 324
Occurrence 324
Alterations 324
Humite group 325
Chondrodite, humite, and clinohumite 325
Occurrence 325
Alterations 325
Tourmaline 326
Occurrence 326
Alterations 326
Staurolite 327
Occurrence 327
Alterations 327
Zeolite group 329
Thomsonite, hydronephelite, natrolite, mesolite, scolecite, analcite, apophyllite, epistilbite, heulandite, stilbite, phillipsite, harmotome, gismondite, chabazite, gmelinite, and laumontite 329
Occurrence 331
Alterations 333
Mica group 336
Muscovite, paragonite, biotite, and phlogopite 336
Muscovite 336
Occurrence 336
Alterations 337
Paragonite 338
Occurrence 338
Alterations 338
Biotite 339
Occurrence 339
Alterations 339
Phlogopite 343
Occurrence 343
Alterations 343
Clintonite group 344
Margarite, chloritoid, and ottrelite 344
Occurrence 344
Alterations 345

CHAPTER V.—MINERALS—Continued. Page.
Section 3. Rock-making minerals—Continued.
The silicates—Continued.
Chlorite group 345
Amesite, corundophilite, prochlorite, clinochlore, and penninite 345
Occurrence 346
Alterations 347
Serpentine-talc group 348
Serpentine and talc 348
Serpentine 349
Occurrence 349
Alterations 349
Talc 350
Occurrence 350
Alterations 351
Glauconite 351
Occurrence 351
Alterations 351
Kaolin group 352
Occurrence 352
Alterations 352
Summary of alteration of silicates 352
The titanates 354
Titanite and perovskite 354
Titanite 354
Occurrence 354
Alterations 355
Perovskite 355
Occurrence 355
Alterations 355
The phosphates 356
Apatite 356
Occurrence 356
Alterations 356
The sulphates 357
Anhydrite and gypsum 357
Anhydrite 357
Occurrence 357
Alterations 357
Gypsum 357
Occurrence 357
Alterations 358
Section 4. General statements 359
Physical-chemical factors upon which nature of alterations depends 359
Chemical composition 359

CHAPTER V.—MINERALS—Continued.
Section 4. General statements—Continued.
Physical-chemical factors upon which nature of alterations depends—Continued.
Chemical composition 359
Chemical composition of adjacent minerals 359
Chemical composition of circulating solutions 359
Specific gravity 360
Symmetry 360
Specific gravity and symmetry 361
Heat reactions 362
Pressure and volume 363
Reversible reactions 366
Section 5. Tables 369
Table A. Sources of minerals 369
Table B. Alteration products of minerals 372
Table C. Chemical reactions and volume changes 375
Table D. Classification of alterations, with volume changes 395
CHAPTER VI.—THE BELT OF WEATHERING 409
Belt of weathering defined 409
Form of level of ground water 411
Amount and source of water in belt of weathering 413
The circulation 416
Downward movements of water 417
Upward movements of water 419
Molecular attraction 419
Vegetation 422
Variation in level of ground water 423
Precipitation, seepage, and evaporation 423
Uplift and subsidence 426
Denudation and valley filling 426
Influence of man 427
Barometric pressure 428
Temperature 428
General statements 429
Metamorphism in the belt of weathering 429
Variable materials and conditions of belt of weathering 429
Mechanical work 431
Water, ice, and wind 432
Change in temperature 434
Change from water to ice 440
Plants 444
Lichens, mosses, etc 444
Cacti 445
Grasses, grains, and vegetables 445
Shrubs and trees 445

CHAPTER VI.—THE BELT OF WEATHERING—Continued. Page.
Metamorphism in the belt of weathering—Continued.
Mechanical work—Continued.
Animals ... 447
Earthworms ... 448
Ants, termites, and other insects ... 448
The larger burrowing animals ... 449
Man ... 450
General statements ... 451
Chemical work ... 451
The agents ... 452
Plants ... 452
Plants, alive ... 452
Plants, dead, and bacteria ... 455
Animals ... 456
Animals, alive ... 456
Animals, dead, and bacteria ... 457
Work of solutions ... 457
Joint work of agents of weathering ... 461
Oxidation ... 461
Oxidation of organic compounds ... 461
Oxidation of carbon and hydrogen ... 461
Oxidation of nitrogen ... 465
Oxidation of inorganic compounds ... 466
Iron ... 467
Sulphur ... 468
General statements ... 469
Carbonation ... 473
Hydration and dehydration ... 481
Oxidation, carbonation, and hydration ... 483
Solution ... 484
Deposition ... 487
General statements ... 487
Contact metamorphism ... 488
Direct contact effect ... 489
Indirect contact effect, or work of fumaroles and solfataras ... 490
Relations of disintegration to decomposition and solution ... 494
Regions favorable to prominence of disintegration ... 496
Arid regions ... 496
Regions of high latitude ... 498
Regions of marked topographic relief ... 499
Regions of sparse plants and animals ... 500
Regions near the sea ... 500
Regions favorable to prominence of decomposition ... 501
Humid regions ... 501
Regions of low latitude ... 502

CHAPTER VI.—THE BELT OF WEATHERING—Continued. Page.
Metamorphism in the belt of weathering—Continued.
Relations of disintegration to decomposition and solution—Continued.
Regions favorable to prominence of decomposition—Continued.
Regions of moderate topographic relief 502
Regions of abundant plants and animals 503
Regions remote from the sea 504
General statements 504
Change in chemical composition of the rocks 507
Order of decomposition of the minerals, and the end products 518
Total gains and losses in weathering, and changes in volume 522
Emphasis and retention of structures and textures 524
Obliteration of structures and textures 526
Surfaces of weathering 527
Depth and degree of weathering 529
Rate of weathering 532
Forces and agents at work in weathering 532
Materials weathered 532
Chemical composition 532
Mineral composition 533
State of aggregation 533
Thickness of the belt of weathering 534
Stage of weathering 535
Distribution of dissolved materials 536
Material abstracted by plants 537
Material transferred to belt of cementation 538
Material permanently abstracted by run-off 538
Material dissolved, transported, and reprecipitated in belt of weathering 539
Concentration at and near the surface 543
Concentration by underground circulation 543
Concentration by circulation mainly confined to belt of weathering 544
Concentration by circulation extending into belt of cementation 550
Concentration by overground circulation 551
Distribution of residual materials 554
Relations of belt of weathering to sedimentary rocks 555
Belt of weathering the source of sedimentary rocks 555
Material transported in suspension 556
Material transported in solution 557
Material transported in suspension and solution 558
Rocks produced from material of belt of weathering without transportation to the sea 559
Transition between belt of weathering and belt of cementation 560
CHAPTER VII.—THE BELT OF CEMENTATION 562
Belt of cementation defined 562
Boundaries of belt of cementation 565

CHAPTER VII.—THE BELT OF CEMENTATION—Continued. Page

Condition of water in belt of cementation 566
Amount of water in belt of cementation 569
Circulation of water in belt of cementation 571
Vigor of circulation 571
Character of circulation 572
Limiting formations 576
Gravity 578
Increase of temperature with depth 578
Relative lengths of vertical and horizontal components 579
Preferential use of large channels 580
Resultant circulation 582
General statement 589
Temperature of entering and issuing water, and transfer of heat 589
Variable materials and conditions of belt of cementation 594
Work in belt of cementation 594
Mechanical work 594
Consolidation 595
Strain within elastic limit 597
Strain beyond elastic limit 599
Chemical work 602
Chemical changes 602
Oxidation 604
Carbonation 608
Hydration 612
Solution and deposition 612
Quantitative relations between solution and deposition 613
Resultant processes 617
Cementation 617
Cementing substances 621
Oxides 622
Silica 622
Iron oxides 623
Aluminum oxides 624
Carbonates 624
Calcite and dolomite 624
Siderite 625
Silicates 625
Sulphides 627
Distribution of elements in cementing minerals 627
Distribution of cementing minerials 628
Causes of cementation 629
Expansion reactions 631
Contributions from igneous rocks 634
Selective precipitation 634
Diffusion 636
Conclusion 639

CHAPTER VII.—THE BELT OF CEMENTATION—Continued. Page.
Work in belt of cementation—Continued.
Chemical work—Continued.
Resultant processes—Continued.
Metasomatism 640
Definition 640
Extent of process 640
Conditions favorable to metasomatism 641
Minerals produced 642
Growth of large individuals and preservation of textures 643
Segregation of individual minerals 645
Igneous work 646
Injection 646
Combinations and relations of mechanical work, chemical work, and igneous work 653
Changes of chemical composition 655
CHAPTER VIII.—THE ZONE OF ANAMORPHISM 657
Definition of zone 657
Condition of water 659
Quantity of water 661
Circulation of water 661
Variable materials and conditions 668
Work in zone of anamorphism 670
Mechanical work 670
Welding 670
Strain within elastic limit 671
Strain beyond elastic limit 673
Chemical work 675
Chemical changes 676
Deoxidation 676
Silication 677
Dehydration 679
Solution and deposition 680
Resultant processes 681
Cementation 681
Metasomatism 682
Minerals formed 683
Alterations in connection with mass-mechanical action 685
Recrystallization 686
Facts of recrystallization 686
Theory of recrystallization 690
Recrystallization lags behind deformation 696
Conclusion 698
Alterations under mass-static conditions 698
Development of porphyritic textures 699
Regeneration of mineral particles 705

Chapter VIII.—The Zone of Anamorphism—Continued. Page.
Work in zone of anamorphism—Continued.
Igneous work 707
Injection 707
Manner of intrusion 708
Resultant metamorphism 711
Factors controlling metamorphism 711
Size of intrusive masses 711
The temperature 712
Amount of water present 712
Composition of intrusive and intruded rocks 713
Metamorphic effects 716
Structures 716
The minerals 717
Pegmatites 720
Fusion and absorption 728
Combinations and relations of the various processes 736
Relations of granulation and recrystallization 737
Character of material 738
Temperature 740
Pressure and rapidity of deformation 741
Water content 741
Rock flowage 748
Meaning of rock flowage 748
Conclusion 759
Meaning of rock cleavage 760
Effect of rock flow on textures and structures 760
Rock flowage and mashing 762
Changes in chemical composition 764
Relations of zone of anamorphism to zone of katamorphism 766
Comparative energy required for deformation in zones of katamorphism and anamorphism 769
Conclusion 774
Chapter IX.—Rocks 775
Use of some general terms applied to metamorphic rocks 776
Meta 776
Apo 776
Slate and schist 778
Slate 778
Schist 779
Gneiss 782
General statements 783
Sedimentary rocks 784
Nonfragmental class 787
Nitrate order 787
Niter family 787

CHAPTER IX.—ROCKS—Continued. Page.
Sedimentary rocks—Continued.
Nonfragmental class—Continued.
Sulphate order ... 788
Gypsum and anhydrite family ... 788
Chloride order ... 789
Rock-salt family ... 789
Carbonate order ... 791
Calcium-magnesium carbonate family and metamorphosed equivalents ... 791
Limestones ... 791
Source of material of limestones ... 791
Organic precipitates ... 792
Chemical precipitates ... 793
Springs and streams ... 793
Inland seas with no outlets ... 793
Possible chemical precipitates in the ocean or in seas connected with the ocean ... 793
Metamorphism of organic and chemical calcium carbonate deposits ... 795
Dolomite ... 798
Origin of dolomite ... 798
Dolomite due to replacement of calcium by magnesium ... 798
Conclusion ... 802
How and why dolomitization occurs ... 802
Dolomitization before limestone emerges from the sea ... 802
Dolomitization after limestone emerges from the sea ... 804
Marble ... 808
Cherty limestones, cherty dolomites, and cherty marbles ... 816
Silicated marbles ... 820
Silicate rocks ... 822
General statements ... 823
Iron-bearing carbonate family and metamorphosed equivalents ... 823
Siderite, ankerite, and parankerite ... 823
Origin of siderite, ankerite, and parankerite ... 824
Ferruginous shales, ferruginous cherts, and jaspilites ... 829
Ferruginous shales ... 830
Ferruginous cherts ... 830
Jaspilites ... 831
Actinolitic and grüneritic marbles ... 833
Actinolite-magnetite-quartz rocks and grünerite-magnetite-quartz rocks. 834
General statements ... 841
Oxide order ... 842
Iron-oxide family ... 342
Limonite ... 842
Hematite ... 843
Magnetite ... 845

CHAPTER IX.—ROCKS—Continued. Page.
Sedimentary rocks—Continued.
Nonfragmental class—Continued.
Oxide order—Continued.
Silica family 847
Chert 847
Rearrangement of chert 849
Fragmental class 853
Psephite order 853
Pebble, gravel, and bowlder deposits 853
Conglomerates 855
Schist-conglomerate and gneiss-psephite, or conglomerate-schist and psephite-gneiss 857
Psammite order 860
Quartz-sand family 860
Quartz-sand rock 860
Sandstone 864
Quartzite 865
Schist-quartzite or quartzite-schist 868
Quartz-feldspar-sand family 870
Quartz-feldspar sand 870
Arkose 874
Schist-arkose and gneiss-arkose, or arkose-schist and arkose-gneiss 875
Ferromagnesian-sand family 877
Ferromagnesian sands 877
Grits 879
Graywacke 880
Slate-graywacke, schist-graywacke, and gneiss-graywacke; or graywacke-slate, graywacke-schist, and graywacke-gneiss 883
Pelite order 886
Mud family 886
Shale family 892
Slate-pelite, schist-pelite, and gneiss-pelite; or pelite-slate, pelite-schist, and pelite-gneiss 894
Development of minerals of slates 898
Development of minerals of schists and gneisses 899
Igneous rocks 904
CHAPTER X.—THE RELATIONS OF METAMORPHISM TO STRATIGRAPHY 907
Introductory 907
Discrimination between metamorphosed sedimentary and metamorphosed igneous rocks. 908
Cases of confusion 909
Criteria for discrimination 912
Relations of metamorphic sedimentary rocks to stratigraphy 917
Variation in metamorphism 917
Upon what variations are dependent 917
Resulting variations 918

CHAPTER X.—THE RELATIONS OF METAMORPHISM TO STRATIGRAPHY—Continued. Page
Relations of igneous rocks to stratigraphy 922
Relations of rock flowage to mountain making 924
CHAPTER XI.—RELATIONS OF METAMORPHISM TO THE DISTRIBUTION OF THE CHEMICAL ELEMENTS. 932
Composition of the lithosphere 932
Table of analyses of igneous and crystalline rocks 934
Table giving symbols, atomic weights, and proportions of the twenty-three most abundant elements in the outer 10 miles of the earth 936
Table showing the amounts of the eleven most common oxides of the lithosphere, as estimated in 1891 and 1900 937
Composite analyses of sedimentary rocks 938
Constituents of meteorites 945
Redistribution of the chemical elements 947
Oxygen 948
Sulphur 957
Silicon 959
Carbon 962
Amount of carbon 962
Segregation of carbon 964
Segregation by carbonation 964
Segregation in carbonaceous deposits 966
Sources of segregated carbon 967
Titanium 974
Phosphorus 975
Chlorine 978
Nitrogen 980
Hydrogen 981
Aluminum 983
Iron 986
Manganese 989
Calcium 990
Magnesium 992
Sodium 996
Potassium 999
Barium, strontium, chromium, nickel, lithium, fluorine, bromine 1002
General statements 1002
CHAPTER XII.—THE RELATIONS OF METAMORPHISM TO ORE DEPOSITS 1004
Part 1. General principles 1004
Introductory 1004
Classification of ore deposits 1005
Deformation of the lithosphere 1005
Zone of fracture, or zone of katamorphism 1005
Openings of zone of fracture 1006
Form and continuity of openings 1007
Size of openings 1008
Volume of openings 1008

CHAPTER XII.—THE RELATIONS OF METAMORPHISM TO ORE DEPOSITS—Continued. Page.
Part I. General principles—Continued.
Deformation of the lithosphere—Continued.
Zone of fracture, or zone of katamorphism—Continued.
Chemical reactions 1008
Zone of combined fracture and flowage 1009
Zone of flowage, or zone of anamorphism 1011
Openings of zone of flowage 1012
Reactions of zone of flowage 1012
Relations between zones of deformation 1012
Effects of deformation and chemical changes upon temperature 1013
Volcanism 1014
Circulation and work of solutions 1017
Circulation of gaseous solutions 1018
Circulation in belt of weathering 1018
Circulation in belt of cementation 1019
Circulation in zone of anamorphism 1020
Circulation of aqueous solutions 1021
Circulation in zone of fracture, or zone of katamorphism 1022
Belt of weathering 1023
Belt of cementation 1024
Circulation in zone of combined fracture and flowage 1028
Circulation in zone of flowage, or zone of anamorphism 1029
Source of the metals 1030
Part II. Segregation of ores 1036
General statements 1036
Division A. Ores produced by processes of sedimentation 1037
Ores formed by chemical precipitation 1037
Ores formed by mechanical concentration 1038
Metamorphic alterations of sedimentary ores 1039
Division B. Ores produced by igneous processes 1043
Division C. Ores produced by processes of metamorphism 1052
Group A. Ores deposited by gaseous solutions 1052
Group B. Ores deposited by aqueous solutions 1058
I. Source of aqueous solutions 1065
II. Source of metals for ores deposited from aqueous solutions 1069
III. Work of aqueous solutions in segregating ores 1072
Subclass 1. Ores precipitated from ascending aqueous solutions 1072
Solution of the metals 1073
Transportation of the metals 1075
Precipitation of the metals 1081
Precipitation by decrease of temperature and pressure 1081
Precipitation by mingling of solutions 1082
Precipitation by reactions between solutions and solids 1086
General statements 1088

CHAPTER XII.—THE RELATIONS OF METAMORPHISM TO ORE DEPOSITS—Continued. Page.
Part II. Segregation of ores—Continued.
Division C. Ores produced by processes of metamorphism—Continued.
Group B. Ores deposited by aqueous solutions—Continued.
III. Work of aqueous solutions in segregating ores—Continued.
Subclass 1. Ores precipitated from ascending aqueous solutions—Cont'd.
Compounds deposited by ascending solutions 1088
Metals 1089
Gold 1089
Solution 1089
Precipitation 1091
Silver 1099
Solution 1099
Precipitation 1100
Copper 1101
Solution 1101
Precipitation 1101
Sulphides 1104
Solution of sulphides 1106
Precipitation of sulphides 1108
Precipitation of sulphides transported as such 1109
Precipitation of sulphides transported as oxidized salts. 1110
General statements 1117
Tellurides 1119
Oxides 1125
Magnetite 1126
Zincite 1126
Franklinite 1126
Hematite 1126
Cassiterite 1127
Carbonates 1128
Silicates 1129
Criteria for discriminating deposits of the deep circulation 1132
General statements 1138
Subclass 2. Ores precipitated from ascending and descending aqueous solutions 1139
Association of lead, zinc, and iron compounds 1144
Facts of occurrence 1144
Second concentration 1147
Oxidized ores 1147
Sulphide ores 1148
Galena 1148
Sphalerite 1151
Marcasite and pyrite 1152
General statements 1153

CHAPTER XII.—THE RELATIONS OF METAMORPHISM TO ORE DEPOSITS—Continued. Page.
Part II. Segregation of ores—Continued.
Division C. Ores produced by processes of metamorphism—Continued.
Group B. Ores deposited by aqueous solutions—Continued.
III. Work of aqueous solutions in segregating ores—Continued.
Subclass 2. Ores precipitated from ascending and descending aqueous solutions—Continued.
Association of copper and iron compounds 1158
Association of silver and gold with base metals 1166
Silver 1166
Gold 1169
Concentration by reaction upon sulphides compared with metallurgical concentration 1174
Other reactions of descending solutions 1175
Second concentration favored by large openings near the surface ... 1177
Depth of effect of descending waters 1179
Illustrations of secondary enrichment and diminution of richness with depth 1182
General statements 1189
Subclass 3. Ores precipitated from descending aqueous solutions 1193
Iron ores 1193
Manganese ores 1198
IV. Special factors affecting the concentration of ores 1199
Variations in porosity and structure 1200
Distribution and size of openings 1201
Complexity of openings 1202
Preexisting channels and replacements 1203
Impervious strata at various depths 1207
Pitching troughs and arches 1211
General statements 1216
Character of topography 1217
Effect of vertical element 1217
Effect of horizontal element 1218
Physical revolutions 1221
V. General statements 1223
VI. Ore shoots 1223
General statements 1230
Summary and conclusion 1232
INDEX 1245

ILLUSTRATIONS.

Page.

PLATE I. Fairview Dome, Sierra Nevada, from the north 436

II. *A*, Parallel veins of calcite, Great Basin; *B*, Biotitic granite, showing garnet surrounded by lenticular areas deficient in iron-bearing minerals 700

III. Photomicrographs of metamorphic textures 704

IV. Textures of limestones and marble 796

V. Textures of metamorphosed marbles 810

VI. Photomicrographs of limestone and marbles 814

VII. Photomicrographs of iron-bearing rocks 836

VIII. *A*, Unaltered Newark conglomerate from Virginia, after Keith; *B*, Schist conglomerate from Felch Mountain district, Michigan 858

IX. Photomicrographs of sandstone and quartzites 872

X. Photomicrographs of graywackes 888

XI. Photomicrographs of pelites 902

XII. *A*, Vein quartz, Banner mine, California; *B*, Secondary galena and blende in ores from Missouri 1156

XIII. Iron-ore deposits in pitching troughs 1196

FIG. 1. Change of volume resulting from solution, and relations of solution and pressure 78

2. Quantitative relations between solution and temperature 80

3. Triangular cross sections of pore space 132

4. Spheres packed in the most compact manner possible 133

5. Relations of level of ground water to topography and to surface drainage 410

6. Effect of unequal heating of the surface of a rock 434

7. Ideal horizontal section of the flow of ground water from one well to another 570

8. Ideal vertical section of the flow of ground water from one well to another 571

9. Ideal vertical section of the flow of ground water entering at one point on a slope and issuing at a lower point 573

10. Ideal vertical section of the flow of ground water entering at three points and issuing at a single point 574

11. Ideal vertical section of the flow of ground water entering at many points along a slope and issuing at a single point at a lower elevation 575

12. Ideal section illustrating the chief requisite conditions of artesian wells 577

13. Part of a thin section of a quartz-schist showing liquid- and gas-filled cavities of a secondary nature; Black Hills, South Dakota 620

14. Enlargement of feldspar fragment 626

15. Enlargement of hornblende fragment 626

16. Clastic quartz penetrated by serpentine 643

Page.

FIG. 17. Granulation of feldspar and gradation between undulatory extinction and granulation 674
18. Granulation of quartz in a rock in which the feldspar is but little affected 674
19. Liquid-filled cavities extending across several quartz individuals without change of direction 746
20. Diagram showing possible relation of old and new grains of recrystallized rocks 752
21. Diagrams illustrating mass deformation of a rock 769
22. Sketch of oval irregular grains of calcite with longer diameters parallel 810
23. Graywacke undergoing serpentinization along cracks 882
24. Conglomerate deposited in depression produced by erosion of basic dike through gneiss 923
25. Diagrams illustrating the manner in which deformation in the zone of flowage may concentrate crustal shortening in the zone of fracture 928
26. Ideal vertical section of the flow of water entering at a number of points on a slope and passing to a valley below through a homogeneous medium interrupted by two open vertical channels, one on the slope and one in the valley 1076
27. Ideal section showing underground circulation in which no water anywhere ascends before issuing at the surface 1080
28. Cross section of banded vein near the London shaft, Mineral Point, Colorado 1135
29. Diagrammatic section of Enterprise mine, Colorado, and its blanket pay shoot 1208
30. Diagram illustrating mingling of circulations of two limestones separated by a shale. 1209
31. Ideal vertical section of flow of underground water in the Galena limestone of the upper Mississippi Valley 1210
32. Ore deposit in limestone beneath impervious shale, Elkhorn mine, Montana 1214

LETTER OF TRANSMITTAL.

DEPARTMENT OF THE INTERIOR,
UNITED STATES GEOLOGICAL SURVEY,
SECTION OF PRE-CAMBRIAN AND METAMORPHIC GEOLOGY,
Madison, Wis., April 30, 1903.

SIR: I transmit herewith the manuscript of a treatise on metamorphism, to be published as a monograph.

This treatise is an attempt to reduce the phenomena of metamorphism to order under the principles of physics and chemistry, or, more simply, under the laws of energy. The first nine chapters treat of metamorphism; the last three chapters, of the relations of metamorphism to stratigraphy, to the redistribution of the elements, and to ore deposits.

In the preparation of this monograph I have had important assistance from various sources. The late Prof. George H. Williams, of Johns Hopkins University, before his death had begun to accumulate material and notes upon metamorphism. He had made a careful abstract of the most important literature on the subject; also a draft, consisting of about twenty pages of manuscript, of a first chapter. All of this material Mrs. Williams turned over to me. The summary of literature prepared by Dr. Williams has been of very great service. To this dear friend, the first great teacher of petrology in this country, I dedicate this volume.

In the actual preparation of the manuscript I have had the assistance of a number of men, and of a considerable number of advanced students. In the earlier work Dr. C. K. Leith aided me much by looking up and summarizing literature and by offering many valuable suggestions. Later Mr. W. N. Smith continued this work. To the discriminating judgment of Dr. Leith and Mr. Smith I am greatly indebted. Mr. A. T. Lincoln has made all the numerical computations in reference to the volume relations of original and secondary minerals, and Mr. R. M. Chapman has verified Mr. Lincoln's work. While these are the men who have assisted me most, a number of graduate students, both at the University of Wisconsin and at the University of Chicago, have helped in various ways.

Geologists who write in other languages than English will have just cause for complaint because of scant reference to publications on metamorphism in such languages, but the arduous work of preparing this treatise has taxed my eyes to the utmost without going exhaustively through foreign literature.

If this attempt to treat one phase of the phenomena of geology from the point of view of energy proves successful, I shall hope that it will lead to similar treatment of other parts of this great science.

Very respectfully, your obedient servant,

CHARLES RICHARD VAN HISE.

Hon. CHARLES D. WALCOTT,
Director of United States Geological Survey.

A TREATISE ON METAMORPHISM.

By Charles Richard Van Hise.

CHAPTER I.

INTRODUCTION.

Following Powell, I shall regard the earth as composed of four spheres—the atmosphere, the hydrosphere, the lithosphere, and the centrosphere.[a] The terms atmosphere and hydrosphere need no definition. The term lithosphere, as here used, will be confined to that portion of the outer part of the earth which is within the limits of observation. How far below the surface observation extends is somewhat uncertain; but it is certain that, in consequence of deformation and denudation, we may observe rocks which have been several thousands of meters below the surface. Clarke suggests that the zone of observation be defined as extending to a depth of 10 miles (16 kilometers) below the level of the sea.[b] Whatever distance be taken as the limit of the zone of observation, it is certain that such distance is but a very small fraction of the radius of the earth. All the earth below this fraction will be considered as the centrosphere; but no hypotheses are advanced in respect to any essential difference in character between the material of the lower part of the lithosphere and that of the upper part of the centrosphere.

GENERAL NATURE OF ALTERATIONS.

The data of geology have become so numerous as to be almost unmanageable. Not many decades ago it was possible for a geologist to have a

[a] Powell, J. W., Physiographic processes: Nat. Geog. Mon., vol. 1, No. 1, 1895, p. 1.

[b] Clarke, F. W., The relative abundance of the chemical elements: Bull. U. S. Geol. Survey No. 78, 1891, p. 34.

reasonably full and satisfactory knowledge, not only of the known principles of geology, but of the observed phenomena in the parts of the world which had been studied. While by many years of work a geologist may still be able to learn the important facts concerning various provinces, it is no longer possible for one man to have anything like complete information as to the local geology of many parts of the world. Not only is this so, but no one geologist can know all the important discovered facts concerning a particular branch of geology. Moreover, in recent years the accumulation of facts has gone on much faster than the development of geological theory. Nowhere is this more true than in the branch of geology known as petrology, and in petrology it is perhaps more true of the phenomena of the alterations of rocks than of any other. Scarcely a paper on petrology appears that does not contain some account of the alterations of minerals or of rocks, but in most cases there is no serious attempt to arrange the observed phenomena in order under recognized principles. Indeed, there is no general set of recognized principles under which the phenomena can be reduced to order.

Some years ago, finding myself lost in the vast accumulation of data, I began to formulate principles applicable to the alterations of rocks. The result of this work is the present treatise, which is an attempt to reduce the phenomena of metamorphism to order under the principles of physics and chemistry, or, more simply, under the laws of energy. It is but a part of the larger task of reducing to order under the same laws the entire subject of physical geology.

As a result of the development of the science of petrology, especially microscopical petrology, it has been ascertained that changes are continually occurring within the rocks constituting the outer part of the earth. This statement is equally applicable to the most porous rocks at the surface of the earth and to the densest rocks as deep below the surface as observation gives exact knowledge. All changes, by whatever forces, agents, and processes caused, and in whatever classes of rocks occurring, whether solidified magmas, chemical precipitates, organic deposits, or mechanical deposits, may be called metamorphism.

Metamorphism, as here used, means any change in the constitution of any kind of rock.

It will be shown that at any given time and place, under any given

set of conditions, minerals tend to form which remain permanent under those conditions. This tendency is more potent with minerals crystallizing from magmas than with minerals which constitute the sedimentary rocks or with the secondary minerals which form by metamorphism. The reason for this is that adjustment to existing conditions is so much more readily accomplished in fluids than in solids; but the tendency to form minerals which are permanent under the existing conditions controls in the solid rocks, although there is a great amount of lag in the process of modification. If adjustment be reached in a given case and if the conditions remain the same, the minerals formed do not again alter, but may remain the same through eons. This is illustrated by the meteorites, the minerals of which may persist without change during the evolutions of stellar systems. However, when an important change of conditions occurs, as when a meteor gives up its separate existence in the interstellar spaces and joins a planet, as the earth, readjustment begins at once.

Although the changes of conditions upon the earth are not so great as the change when a meteor falls to the earth, the range of conditions upon the earth is large and varied. The conditions may be those of ordinary pressure and temperature at or near the surface of the earth, or they may be those of very high pressure and temperature, such as exist well below the surface of the earth. A rock mass may alternately be subject to each of these sets of conditions and to various intermediate conditions. Changes of physical conditions result from surficial transfer of material by epigene agents—bringing rocks to the surface here, burying them there—from igneous intrusions, from orogenic movement, and from other causes. The changes upon the earth are therefore profound, although usually slow.

During the changes the rocks are always modified in the direction of adjustment to the new conditions. Such modification of rocks has led to the idea of adaptation to their environment. As conditions change, species of plants and animals are so rapidly modified that at first sight adaptation seems almost perfect. Indeed, so sensitive are plants and animals to their environment that since the theory of evolution gained ascendancy the fact of approximate adaptation is taken for granted. The variety and complexity of the structures, colors, etc., of life forms resulting from adaptation to environment is a constant source of wonder. Almost daily some remarkable structure or form is described, and its existence explained by showing how

it is advantageous to the animal under the conditions in which it lives. Since adaptation is an assumed law, in those cases where there seems to be lack of adaptation, as where some peculiar structure is present which apparently is not of advantage to an animal or plant, it is believed that the facts are not fully known or that the structure was once useful and is a survival. However, the very idea of survival shows that to a certain degree the development of plants and animals lags behind their changing environment. Upon a priori grounds it would be certain that this is the case; and the existence of rudimentary organs, such as the muscles for moving the human ear, which at one time may have had a use, is positive evidence of the lag of organic species during their adaptation to changing environment.

Likewise it is believed that minerals constantly tend to change to forms that are relatively stable under existent conditions. This, however, is accomplished by granulation or recrystallization or some analogous process, and is adaptation only in the sense that the old particles break up into smaller particles or develop into new mineral particles which conform to the existent conditions. Some minerals are stable under a considerable variety of conditions, and therefore are less sensitive to change than are others. For instance, quartz develops directly from an igneous rock, and it also forms as a deposit from water. It persists under both quiescent and dynamic conditions. Other minerals require rather definite conditions for their existence. Such are leucite and olivine, which abundantly form as original minerals in igneous rocks of certain composition, but which readily change under new conditions to other minerals. However, no mineral persists without reference to its environment, and so it may be said that there is a tendency in all mineral substances to form minerals adjusted to the conditions under which they exist. Rocks are composed of aggregates of different minerals. Therefore rocks, like minerals, have a tendency toward adjustment to their environment.

Even if the chemical composition of a small mass, say a cubic millimeter, remains exactly the same, the mineral constituents of the mass may greatly change. At the end of the change the original minerals may not be in the same proportions as before and minerals which did not originally exist in the rock may have formed. But the adjustment of rocks is not confined to redistribution of the elements present in a small space. There may be a change in the average chemical composition of rocks.

Material may be intruded, or may be brought in by water solutions, or may be abstracted by water solutions. By any one of these processes or by any combination of them a considerable change in the chemical composition of a rock may take place.

While it may be safely asserted that all rocks, under all conditions, at all times, are being adapted to their environment, the change in a rock goes on so slowly that its lag behind the change in the environment may be measured by millions of years. Often the lag is so great that the conditions again change before the process of adjustment has made much advancement, and, therefore, before one set of changes is near completion another set is begun. Indeed, a later change in conditions may be a reversal of an earlier change, and, therefore, in the process of adaptation, work done in an early stage may be reversed at a later stage. But even in such a case it is clear that the principle of adaptation applies, just as in the case of many plants and animals, although there may be, in fact, little more than a *tendency* toward adaptation to existent conditions.

Because the adjustment of rock to environment is so slow, in order that it may be approximately complete it is necessary that a rock remain under substantially the same conditions for a very long time. This has happened in some regions in which important mechanical movements have not occurred for a period or an era and the rocks of which have remained buried to a moderate depth for most of the time. Such were the conditions of the ancient volcanics of certain parts of the Lake Superior region. These have escaped important mechanical movement since the beginning of Paleozoic time. They were buried under Paleozoic sediments to a moderate depth. Denudation since the beginning of Cretaceous time brought them to the surface. Finally glacial erosion removed a skin of weathered material and exposed the volcanic rocks, approximately adapted to their past environment, that of the belt of cementation under quiescent conditions. (See Chapter VII, pp. 594 et seq.) So far as they have reached the surface they are subject to a new set of conditions; and a new cycle of change, begun at the end of the Glacial epoch, but not far advanced, is in progress.

In considering metamorphism, the fundamental hypothesis of geology will be applied as in other branches of the subject. That is to say, the Huttonian principle, that the present is the key to the past, is

assumed. Where certain phenomena are now produced by certain combinations of forces and agents, and by these only, and similar phenomena are found in the rocks long since formed, it is assumed that the like phenomena, present and past, are due to essentially the same combinations of forces and agents. For instance, if alterations of a certain kind are now being produced by a complex set of geological factors, and by these only, where similar alterations are found in ancient rocks it is assumed that they are due to practically the same combination of the forces and agents of alteration.

But the above statement does not imply that the changes are now taking place with the same speed as that with which they occurred in the past, as might have been held by Lyell; nor is it assumed that the various forces and agents have the same relative values. Indeed, it is believed to be highly probable that there have been changes in the rate of alteration of rocks and in the nature and effectiveness of the factors producing the alterations.

While the Huttonian principle is of service in the study of metamorphism, the alterations of rocks take place so slowly that it does not have nearly the value that it has in the study of the work of the epigene agents, such as air and water and ice; nor the value it has in the study of such hypogene agents as volcanoes and earthquakes.

Many of the rock alterations are now taking place under conditions which can not be directly observed, but must be inferred from the records of the change. This statement applies to all changes below a mile in depth, and it is very largely applicable to all but the mere outer film of the rocks, for most excavations and cuttings are not deeper than a few score or a few hundred feet and the deepest shafts are but little over a mile. Fortunately it frequently happens that in a rock formation now at the surface the results of various stages of change under deep-seated conditions are preserved, so that the character of the alterations and the nature of the forces and agents which have produced them may be inferred from a close study of the different stages of alteration.

In such cases, instead of observing the forces and agents accomplishing certain results, and of reasoning that similar results produced in the past are due to these forces and agents, we observe the results at various stages of development and infer from them the nature of the forces and agents producing them; we then infer that similar forces and agents are at work

beyond the zone of observation, accomplishing at the present time similar results. This is a complete reversal of the Huttonian method. Hence, in treating of metamorphism we must argue both from the present to the past and from the past to the present. By studying the action of the forces and agents now at work in the zone of observation and the stages of alteration preserved in the rocks brought into the zone of observation we are able to push the boundaries of the known for a certain distance into the domain of the unknown, and infer with considerable certainty the nature of the changes which have taken place in the far-distant past and of those which are now taking place but which we can not directly observe.

It will be generally agreed that the majority of the altered rocks, including a large portion of the schists and gneisses, have been metamorphosed from aqueous and igneous rocks like those now being produced. This is in accordance with the Huttonian principle. But some may hold that the most ancient of the schists and gneisses, those of the so-called Basement Complex, had a different origin. For instance, it has been held by some that these ancient rocks are direct precipitates in a primeval ocean. On later pages it will be seen that the most ancient schists and gneisses are in all respects like those produced from more recent rocks by the processes of alteration, and therefore that the probable, but not certain, inference is that they were produced from rocks not fundamentally unlike those now being formed by processes of change not radically different from those now at work. But in ascertaining the forces and agents and their method of work in both the ancient and the modern rocks, we must for the most part follow the reversal of the Huttonian principle—i. e., argue from past results as to the nature and method of work of present forces and agents.

Whatever the origin of rocks—whether solidifications from magmas, chemical precipitates, organic deposits, or mechanical deposits—as already noted, they may be altered so as to modify their structures, so as to change their mineral composition, and so as to change their chemical composition. In place of the original characteristic structures of the igneous rocks, such as flowage structure and massive structure, and in place of the original structures of the sedimentary rocks, such as bedding, there may be produced secondary structures, such as cleavage, fissility, joints, slatiness, schistosity, and gneissosity. In place of the original textures of igneous rocks, such as granolitic, porphyritic, ophitic, and poikilitic, and in place

of the original textures of sedimentary rocks, such as granular and oolitic, there may be produced textures characteristic of the metamorphic rocks, such as cataclastic, parallel orientation, etc. The alteration may result in the change to minerals all of which may wholly differ from any of the original minerals, or it may take place by recrystallization without change in mineral character, as in the case of the formation of marble from limestone. Chemical change may result in the addition of constituents, as in the case of oxidation and hydration of compounds already existing, or in the deposition of additional material in the interstices, or in the abstraction of material. Any given mineral may gain additional elements, or a greater proportion of some of the elements; it may lose a part or all of some of its elements, or it may be wholly replaced by another mineral. While the chemical composition of the rock may be greatly affected by such changes, in other cases the alterations may result merely in a redistribution of the elements without affecting the average composition of the rock, as in the case of marmorization, some cases of devitrification, various cases of metasomatism, etc.

After one set of changes has taken place, or while they are in progress, a change of physical conditions may come about in consequence of which a different set of changes may be set up. Thus rocks may be partly modified under mass-static conditions and subsequently modified under mass-mechanical conditions. They may be modified near the surface of the earth, and as a result of burial be later modified at much greater depth; or they may be modified at great depth, and as a result of erosion be brought near the surface and there be again modified. Therefore one set of changes may be superimposed upon another. In many cases it is certain that rocks have gone through several very complex sets of modifications. For instance, a rock may be modified under conditions at the surface, afterwards be buried under other strata and thus pass into a deep zone, where it may be modified in a different manner, and still later, as a result of denudation, be brought to the surface and in the passage undergo successive alterations in intermediate belts, and when it reaches the surface once more be altered by the same forces and agents as at first. Substantially this history has been gone through by the jaspilites of the Lake Superior region. (See pp. 831–833.) Many other rocks have had an equally intricate but very different history.

CLASSIFICATION OF METAMORPHISM.

The forces of metamorphism are chemical energy, gravity, and heat and light. The agents of metamorphism are gases, liquids, and organic compounds.

A critical examination of the published classifications of metamorphism shows that the kinds of metamorphism recognized are based upon the idea that one force or agent or process is dominant in the production of a particular kind of rock. But in all of the various kinds of metamorphism ordinarily recognized in classifications, such as thermo-metamorphism, hydro-metamorphism, chemical metamorphism, static metamorphism, pressure metamorphism, dynamo-metamorphism, regional metamorphism, and contact metamorphism, all of the forces above mentioned are required, and also the chief agent, water. There is no metamorphism of a rock without the presence of heat, and hence all metamorphism is partly thermo-metamorphism; there is no metamorphism without the presence of water solutions, and hence all metamorphism is partly hydro-metamorphism; there is no metamorphism in which chemical action does not enter, and hence all metamorphism is partly chemical metamorphism; there is no metamorphism without motion, and hence, in an exact sense, all metamorphism is dynamic. In the alterations of rocks the forces of metamorphism in each case produce atomic, molecular, and mechanical changes.[a] When it is realized that in all the varieties of metamorphism mentioned chemical action, heat, and dynamic action enter as important factors, and that water is present and active wherever metamorphism occurs, it becomes self-evident that the classifications ordinarily given are not satisfactory. Moreover, the classifications involve different factors not belonging to the same category, some being physical, some chemical, some geological, some referring to an agent, others to a cause. For instance, thermo-metamorphism refers to heat; hydro-metamorphism refers to the presence of water; chemical metamorphism refers to the action of chemical forces; static metamorphism and pressure metamorphism refer to quiescent conditions; dynamo-metamorphism refers to conditions of motion; regional metamorphism refers to the extent

[a] If this be true, it is clear that a classification of metamorphism into paramorphism, metatrophy, and metataxis, restricting these terms to atomic, molecular, and mechanical changes, respectively, as proposed by A. Irving, is wholly impracticable. Irving, A., Metamorphism of rocks, London, 1889, pp. 4–5.

of the alterations; and contact metamorphism refers to the contiguity of an igneous rock.

As a matter of fact, all of these different kinds of metamorphism are related in the most intricate manner, and certain metamorphic results which have been attributed to one of these forces, agents, or processes could equally well be attributed to another. For instance, in many cases metamorphism known as thermo-metamorphism might just as well be called hydro-metamorphism, or regional metamorphism be called dynamic metamorphism, or contact metamorphism be called thermo-metamorphism or chemical metamorphism.

It follows from the above that a satisfactory classification of metamorphism based upon chemical forces alone, or physical forces alone, or individual processes, is quite out of the question. It appears to me that the only workable classification of metamorphism is geological. (See pp. 43–44.)

GEOLOGICAL FACTORS AFFECTING THE ALTERATIONS OF ROCKS.

The more important geological factors affecting the alterations of rocks are: Composition; structures and textures; porosity; water and gaseous content; climatic and geographic conditions; time; environment; degree of movement; depth. Many physical factors enter into each of these geological factors.

At present only general statements will be made with reference to these factors, but on later pages the effect of each of them will more clearly appear.

Composition.—In so far as rocks are composed of minerals which are permanent under the existing conditions, or are composed of minerals which may exist under a wide variety of conditions, this is favorable to stability.

Structures and textures.—In so far as there are coarse structures and textures, this is favorable to permanency, for it will be seen that fine material is more readily altered than coarse material.

Porosity.—Porosity has a very important influence upon the rapidity of change. In proportion as rocks are porous the agents of alteration, gases and water, may enter and rapidly circulate. In proportion as they are dense, the amount of water present is small and the circulation is slow.

Hence porosity is favorable to rapid change; density is favorable to stability.

Water and gaseous content.—In proportion as rocks contain water and gas they are readily altered. In proportion as water and gas are absent they are stable.

Climatic and geographic conditions.—The speed of alteration of rocks is affected by their geographical position. The alteration of surface rocks is more rapid in tropical than in arctic regions; it is more rapid in humid than in arid regions; it is more rapid on steep than on gentle slopes; it is more rapid along coasts than in the interior. In short, the nature of the alterations of the upper belt of rocks varies with every varying factor of climate and geography.

Time.—Time is a factor of the very highest importance in metamorphism. Time can not be included among the forces or the agents of metamorphism, but the amount of metamorphism is a function of the time. Where a given set of forces and agents is at work under a given set of conditions, increase of time increases the metamorphism, but not in a direct ratio, for in proportion as adjustment to environment is approached the alterations decrease in speed. The importance of time in geology can not be too strongly emphasized, for a comparatively weak force or agent working through a great length of time may accomplish an almost incredible amount of work. We are accustomed to judge of the efficiency of a force or agent by observations in the chemical or physical laboratory, but the time through which an experiment may be continued in the laboratory is an almost infinitely small fraction of the time through which the forces and agents have been at work in nature. To illustrate, in the chemical laboratory the amount of crystallized silica which can be dissolved in water and transported to another place within the time during which an ordinary experiment is carried on is so small as to be unmeasurable, and yet it is certain that in nature water has dissolved and transported to other places enormous quantities of silica. (See Chapter VII, pp. 622–623.) This illustration enforces the fact that the geologist has very much more time at his command than has the chemist or the physicist. If the geologist ignores this fact, and reasons in reference to the potency of forces and agents in metamorphism as a chemist or physicist would in the laboratory in reference to the same forces and agents, he is certain to fall into very serious

error. The importance of the time factor has been recognized by most geologists with respect to erosion and many of the other geological processes, but it is of even greater importance in metamorphism. Most of the metamorphic processes are very slow indeed, but the amount of time available in a single geological period is great, and the metamorphic results are often stupendous.

In general it may be said that in proportion as rocks are old they are likely to have been greatly altered; in proportion as they are young they are likely to have been little altered. While time is a most important factor in the amount of alteration, time alone, without the other necessary conditions for change, is not sufficient to insure important metamorphic results. Further, when the other conditions are very favorable to change, extensive alteration may take place in a comparatively short time, considering this factor from a geological point of view. It follows, because of variations in other factors than time, that in some regions very ancient rocks may be little modified and in other regions comparatively young rocks may be greatly modified.

Environment.—In many cases environment may be important. If the rocks surrounding a given rock be porous, this condition readily permits the entrance of the agents of alteration—water and gases—and therefore much more profound change may occur than if the rock were surrounded by comparatively impervious material. This is illustrated by the diabase dikes of the Penokee series of Michigan, which where surrounded by the broken rocks of the iron-bearing formation are completely altered, but which where surrounded by the impervious black slates are comparatively unaltered. A further very important factor in environment is the presence of intruded igneous rocks. Igneous rocks, by conduction, may directly heat the adjacent rocks; but of even greater importance is the fact that igneous rocks may furnish solutions to the adjacent rocks or heat the solutions which percolate through them. These illustrations show that the alteration of a rock may be greatly affected by the surrounding rocks.

Degree of movement.—One of the most important of the factors affecting alterations is movement; indeed, the factor of movement is so important that it has frequently been made a basis for a classification of metamorphism. Changes of rocks take place with comparative slowness under conditions of quiescence and take place with comparative rapidity under conditions of

movement. Furthermore, the alterations which occur under dynamic conditions are far more profound than those which take place under static conditions. For instance, very ancient sedimentary rocks which have been undisturbed by orogenic movements may be in almost the original condition in which they were deposited. On the other hand, rocks of comparatively recent age which have been in mountain-making areas and been deeply buried may be profoundly modified. Little metamorphosed rocks of great age are illustrated by the St. Peter sandstone of Wisconsin and the unconsolidated Cambrian sands of Russia. Profoundly metamorphosed rocks of comparatively recent age are illustrated by the Eocene and Neocene rocks of the Coast Range of California and the Eocene of the Alps.

Depth.—Rocks at or near the surface of the earth are ordinarily under conditions of slight pressure and low temperature. Rocks at some depth below the surface are under conditions of considerable pressure and temperature. It will be shown that the alterations of a given rock under these varying conditions are very different. Therefore depth is a matter of great consequence in the consideration of metamorphism. Indeed, depth is believed to be the most important of the influences which determine the character of the alterations of rocks. Therefore the geological factor which in this treatise will serve as the primary basis for a classification of metamorphism is the dominant factor of depth. On this basis metamorphism will be classified into (1) alterations in the zone of katamorphism and (2) alterations in the zone of anamorphism. The zone of katamorphism is subdivided into (a) the belt of weathering and (b) the belt of cementation. The zone of katamorphism may be defined as the zone in which the alterations of rocks result in the production of simple compounds from more complex ones. The zone of anamorphism may be defined as the zone in which the alterations of rocks result in the production of complex compounds from more simple ones. The belt of weathering is the belt which extends from the surface to the level of ground water. The belt of cementation is the belt which extends from ground-water level to the zone of anamorphism.

It is to be noted not only that this classification is geological, but that the factor is one which is universally applicable. Geological factors of different kinds, such as movement, contact action, etc., are not introduced. It is therefore clear that the proposed classification follows one law of all

good classifications, viz, that a factor or factors of the same class shall be used throughout as a primary basis. While the primary classification of metamorphism will be based upon depth, it is recognized that there are no sharp dividing lines between the zones and belts. In metamorphism, as in every other branch of geology and of science, there is complete gradation between the phenomena of the various classes.

However, it has been seen that depth is not the only geological factor of consequence in metamorphism. It is recognized that various other geological factors enter into the alteration of a given rock. Moreover, these various factors overlap. In the discussion of the zones of metamorphism the geological factors of subordinate importance will be given proper consideration.

Before considering the general alterations in the zones of katamorphism and anamorphism, and the alterations of the individual minerals and rocks in these zones, it is necessary to consider the forces and the agents of metamorphism from chemical and physical points of view.

It should therefore be recalled that the forces of metamorphism are chemical energy, gravity, and heat and light, and that the agents of metamorphism are gases, liquids, and organic compounds. The rocks are the materials upon which these forces and agents work. The forces of metamorphism are considered in Chapter II, the agents of metamorphism in Chapter III, and the work of these forces and agents upon the rocks in the later chapters.

CHAPTER II.

THE FORCES OF METAMORPHISM.

As already seen, the important forces of metamorphism are chemical energy, gravity, and heat and light.

CHEMICAL ENERGY.

When different compounds are brought together molecular interchange may occur between them. As a result the compositions of the compounds are mutually changed. Such interchange is chemical action. Chemical action usually involves expenditure of chemical energy, which is one of the main original sources of energy; but it will be seen that other forms of energy may be transformed into chemical energy, and chemical action in this way be promoted.

Chemical action may take place between gas and gas, gas and liquid, gas and solid, liquid and liquid, liquid and solid, and solid and solid. Chemical action, or molecular interchange, involves movement between the atoms and molecules. Chemical action therefore never takes place without dynamic action. So far as we know chemical action never takes place without the presence of heat. Under the conditions obtaining in the crust of the earth chemical action is usually promoted by heat and by mechanical action. As chemical action always produces a heat effect, positive or negative, such action may result in the liberation or in the absorption of heat. The heat effect may hasten or retard further chemical action. In so far as chemical action results in the liberation of heat, it usually hastens further chemical action, and therefore promotes metamorphism; in so far as chemical action results in the absorption of heat, it usually retards further chemical action, and therefore stays metamorphism. It is shown (pp. 170–186) that both classes of reactions take place on a very extensive scale.

In consequence of chemical action material may be added to or subtracted from a given mineral. A mineral may alter into two or more other minerals with the simultaneous addition or subtraction of material. Two or more minerals may unite to produce a single mineral. Either of these

changes may take place without addition of material, or added material may be derived from some other particle or particles near or remote. Material subtracted from any given mineral particle may be added to another mineral particle at a greater or less distance. Illustrating the above are the alterations of feldspar into muscovite and quartz, and of olivine into serpentine, magnesite, magnetite, and quartz. Chemical action is in most cases accomplished through solutions. Therefore its detailed discussion is considered in connection with the agents of metamorphism, gaseous solutions, and aqueous solutions. (See Chapter III.)

GRAVITY.

Gravity is now the great dominating force of the universe. Indeed, it is a main original source of energy. Certainly it is the source of energy which has largely controlled the development of the solar system, including the sun and all the planets and satellites. The transformations of gravity into chemical energy, heat, light, and other forms of energy are important factors in the development of the solar system, including the earth. Moreover, gravity still remains as the great dominating force which controls earth movements,[a] both vertical and horizontal, and also the circulation of the water, both overground and underground. By earth movements are meant all movements of the solids or rocks of the earth not in solution. In this broad sense the movement of glaciers is an earth movement.

The direct work of gravity in metamorphism may be considered under two headings—mechanical action and water action.

MECHANICAL ACTION.

Rocks may be stressed within the elastic limit, or the stress may extend beyond the resisting power of the material. In either case the rocks are strained. Strain may occur with or without chemical action. Strain is always accompanied by some transfer of energy into heat. When the rocks are strained the molecules are moved with reference to one another. If the strain be within the elastic limit and chemical change does not take place, the molecules are only slightly farther apart or closer together, and when the stress is removed they may return to their original

[a] Van Hise, C. R., Earth movements: Trans. Wisconsin Acad. Sci., Arts, and Letters, vol. 11, 1898, pp. 512–514.

positions, or nearly so. If under the stress chemical interchange also takes place between the molecules, when the stress is removed the body may still return to nearly its original form. But if the strain extends beyond the elastic limit the form of the body is notably changed, as when a piece of wrought iron or steel is drawn out or when a piece of cast iron is crushed.

Mechanical action may therefore be considered as *molecular* or *mass*. By molecular mechanical action is meant differential movements of the molecules. By mass mechanical action is meant differential movements of large masses of the rocks. Molecular movement also frequently involves differential movements of the atoms. Metamorphism by molecular movement has generally been called static metamorphism. But molecular mechanical action is always accompanied in some degree by mass mechanical action, though this process may be subordinate. The term "dynamic metamorphism" has usually been restricted to alterations in connection with mass deformation. But mass mechanical action is always accompanied by molecular mechanical action as an important and essential concomitant, although this invariable relation has not always been recognized. Further, as mass movement becomes important molecular movement, instead of becoming less important, is likely to be of even greater consequence. There is therefore gradation between molecular mechanical action and mass dynamic action.

MOLECULAR MECHANICAL ACTION.

Molecular mechanical action involves various degrees of movements.

Presumably the lesser movements are the cases of change in crystalline form and of strain within the elastic limit. In the change of a substance from one crystalline form to another—as, for instance, of aragonite to calcite—the movement of the molecules may not involve more than a rearrangement of those which are adjacent. In the case of substances strained within the elastic limit, the molecules are simply pressed slightly closer together or pulled slightly farther apart, and yet these very slight adjustments may have a profound effect upon the physical properties of the materials. For instance, amorphous glass when strained but slightly and well within its elastic limit becomes an anisotropic substance. Leucite crystallizes in the isometric system at high temperatures. As the mineral cools it passes at once into an anisotropic form. The transformation from

one to the other may be seen by alternately heating and cooling this mineral under the microscope. In the foregoing cases, while we can not doubt that movement occurs, the readjustment is molecular, and it is therefore beyond the power of the microscope to determine its character.

It might at first be supposed that such slight movements as are involved in strains within the elastic limit are unimportant, but it is to be remembered that strains of this kind not only affect every mineral particle, but displace the individual molecules with reference to one another, so that the strained masses are affected throughout. While, therefore, it requires polarized light to detect the strained condition in minerals, it is certain that the effect is pervasive. It will be seen (pp. 95–98) that such state of strain is of fundamental importance in the matter of solution and deposition through the agency of solutions.

In a second class of movements there is molecular interchange between substances by which the compounds are modified in composition. Such interchanges involve chemical action. The motions which occur during chemical changes in solids are commonly for such short distances that the naked eye does not discover the relations of the original and secondary minerals. Such movements are microscopic. Chemical interchange may be mainly accomplished by chemical forces and the movement be an incident of this process. On the other hand, mechanical action may be the inciting cause which leads to chemical action. And, finally, the purely chemical and mechanical forces may interact, each promoting the other. The more important chemical reactions resulting from mechanical action are accomplished through the agency of solutions, and hence are treated in Chapter III. But Prof. Walther Spring[a] has shown that chemical changes may be induced by mechanical action alone, without the presence of solutions. For instance, when barium carbonate and solid sodium sulphate were mixed in equal molecular proportions and subjected to a pressure of 6,000 atmospheres a change took place by which 80 per cent of the barium carbonate and sodium sulphate were changed to barium sulphate and sodium carbonate, respectively; and conversely, when barium sulphate and sodium carbonate were mixed together in equal molecular proportions and subjected to a like pressure about 20 per cent was changed

[a] Professor Spring on the physics and chemistry of solids, review by C. F. Tolman, jr.: Jour. Geol., vol. 6, 1898, p. 323.

to barium carbonate and sodium sulphate.[a] In all such changes the fundamental principle controlling is that reactions shall take place which result in smaller volumes. Spring[b] found that in the case of dry reactions induced by mechanical action time is a very important factor, the reactions taking place much more slowly than when compounds are moist and water is an intermediate agent.

MASS MECHANICAL ACTION.

Mass mechanical action (a) may permanently strain the rocks without openings, (b) may strain the rocks with rupture and openings, and (c) may close the openings in rocks and produce welding.

Permanent strain without openings.—In order that permanent strain beyond the elastic limit without openings may take place in the rocks it is necessary that deformation shall occur while the rocks are under a sufficient pressure in all directions to hold the molecules so close together that the molecular attraction is effective. This will be true only where the pressure is greater in all directions than the crushing strength of the rocks. It is well illustrated by Adams and Nicolson's experiment on the deformation of marble while under pressure in all directions.[c] The molecules were held close to one another, and the deformed marble retained considerable strength.

Later we shall see that the process of readjustment may be mechanical or chemical or partly each. When the process is mechanical the mineral particles are usually granulated—that is, finely fractured. When the process is chemical the particles are recrystallized. Also the process of readjustment may be accomplished by any combination of granulation and recrystallization (See pp. 737–748.) Under natural conditions, in order that the pressure in all directions shall be greater than the crushing strength of a rock, it is necessary that it be in the zone of flowage for that rock.

Permanent strain with openings.—When the rocks are strained beyond the elastic limit and the pressure is not greater in all directions than the crushing strength of the rocks, rupture and openings are produced. The ruptures may be regular or irregular. The regular ruptures may be of great extent

[a] Nernst, W., Theoretical chemistry, translated by C. S. Palmer, Macmillan & Co., London, 1895, p. 390.

[b] Spring, op. cit., p. 322.

[c] Adams, F. D., and Nicolson, J. T., An experimental investigation into the flow of marble: Philos. Trans. Royal Soc. London, ser. A, vol. 195, 1901, pp. 363–401.

and wide apart, as in the case of faults; or of moderate extent and width, as in the case of joints and bedding partings; or close together, as in the case of fissility. The irregular ruptures may be continuous and the openings wide, as in the case of the coarse breccias; or discontinuous and the openings small; or so minute as to affect the individual particles, and thus grade into deformations without openings or granulation.

Under natural conditions, in order that the pressure shall not exceed the crushing strength of a rock in all directions, it is necessary that it shall be in the zone of fracture for that rock.

Permanent strain with closing of openings and welding.—Mechanical action may close openings in rocks and weld the separated parts. In this case there is a diminution of volume due to bringing the particles closer to one another. In order that welding shall take place there must be sufficient pressure in all directions to bring the particles so close together that the molecular attractions are effective, or the pressure in all directions must be greater than the crushing strength of the rock.

Of course, the pressure required to satisfy the above conditions for welding depends very greatly upon the character of the material. Moderate pressure may be sufficient to weld material composed of small and weak particles. For instance, moderate pressure of clay may bring many of the minute particles of kaolin so close to one another as to place them within the limits of effective molecular attraction. When the clay is dried the mass becomes harder. This hardening is doubtless due in part to the precipitation of the dissolved material contained by the water and the consequent cementation of the particles, as explained on pages 617–621. In proportion as the particles are coarse, strong, and large, and have relatively few points of contact, the pressure necessary to produce welding increases. To produce deformation with welding of the separated large particles of the strong minerals considerable pressure is necessary.

WATER ACTION.

The movement of water under the force of gravity is of the utmost importance in metamorphism. It is, indeed, the great agent of transportation of material both overground and underground, and is the dominating agent through which metamorphism is accomplished. Its work is fully considered in Chapter III, on "The agents of metamorphism."

HEAT AND LIGHT.

Heat and light are forms of energy of the first importance. It has already been noted that their ultimate source is largely gravity. Heat is always present as a factor in metamorphism, for nowhere upon the surface of the earth nor within the earth is the temperature absolute zero. Other things being equal, the higher the temperature the more rapidly do alterations of rocks take place. Light also affects all parts of the earth at the surface. In metamorphism heat and light should be considered from two points of view—(1) sources of heat and light, and (2) effect of heat and light upon the alterations of rocks.

SOURCES OF HEAT AND LIGHT.

Heat and light agential in the alteration of rocks are derived (a) from the sun, (b) from deep within the earth by conduction or by convection through water or magma, (c) from mechanical action, and (d) from chemical action. The heat from all these sources is important; light, however, is derived chiefly from the sun, that from the other three sources being of little consequence.

THE SUN AS A SOURCE OF HEAT AND LIGHT.

The heat and light of the sun are forces of the first order of magnitude in the alterations of rocks. The effect of these forces needs to be considered in four cycles—the cycle of the solar system, that of the seasons, that of the cyclone, and that of the day.

The solar-system cycle is the most important. This cycle involves two factors—the absolute temperature and change in temperature.

As to the absolute temperature, were it not for the heat and light of the sun it is certain that the temperature of the surface of the earth would not greatly exceed that of the interstellar spaces. Probably it would be —200° C., or even lower. At the present time the temperature of the surface of the earth averages 10° C. (283° C. absolute) or more. Therefore the temperature of all the upper zone of the earth is 200° C., or more, greater than it would be without the heat from the sun. Were it not for this heat the water in the outer zone of the earth would be congealed, and the atomic and molecular energy would be greatly diminished. As a comparatively slight increase of temperature over that prevalent at the surface of the earth increases greatly the speed of alteration of rocks, it is

to be presumed that under such low temperatures changes in rocks would be so slow as to be negligible.

How deep below the surface of the earth the heat of the sun produces an effect can not be accurately determined. It is highly probable that it has an important effect to a depth of thousands of meters, probably beyond the limits of the zone of observation. If the sun were not furnishing heat to the earth, and the increment of increase in temperature were the same as at present (1° C. for 30 meters), and the temperature at the surface were 200° C. lower it would be necessary to penetrate to a depth of 6,000 meters to reach a temperature as high as that at the surface under the present conditions. Below 6,000 meters the temperature would increase approximately as it does now from the surface downward. However, it is not to be supposed that the effects of metamorphism would be the same as those in the outer 6,000 meters at the present time, for the conditions of pressure would be very different. (See Chapter I, p. 43, and Chapter IV, pp. 159–160.) The assumption that the increment of temperature would remain the same were not the sun giving heat to the earth is only approximately true; but when it is remembered that 6,000 meters is an exceedingly small fraction of the earth's radius, it seems probable that the increment of increase of heat with depth in the outer part of the crust of the earth would not be greatly different, even if the sun had long ceased to be a source of heat; but if it were not for the heat of the sun, the temperature of that part of the lithosphere directly under observation would be so low that all chemical changes would be very slow, if indeed they were not inappreciable.

The absolute temperature at the surface is also dependent upon latitude. The average temperature at the warmest tropical regions is about 300° C. absolute, or, stated in the ordinary scale, 27° C.; the average temperature of the coldest polar region where observations have been made (latitude 81° 44′) is 252.9° absolute, or, in the ordinary scale, —20.1° C.[a] At intermediate latitudes there are all gradations between these extremes. At any place the temperature may be presumed to increase with depth from these surface temperatures at the rate of 1° C. per 30 meters.

It would be fruitless to attempt a discussion of the changes of the temperature of the outer part of the earth due to the solar cycle. So far

[a] Hann, Julius, Handbuch der Klimatologie, J. Engelhorn, Stuttgart, 1883, p. 733.

as rock alterations now taking place are concerned, the sun may be regarded as furnishing to the earth a uniform amount of heat.

The seasonal changes of temperature are very important, at the surface ranging from 30° C. or less to as much as 80° C. However, the depth to which the seasonal change produces an effect is not great, probably about 15 meters.

The cyclonic changes of temperature may be very great, ranging from a few degrees to about 70°, but the depth to which these changes extend is slight, probably less than 3 meters.

The diurnal changes in temperature are scarcely less than the cyclonic, ranging from 0 to 50° C. or more; but the depth to which the diurnal changes extend is insignificant, probably but a fraction of a meter.

From the foregoing it is plain that the heat and light derived from the sun are of very great direct importance in the chemical and mechanical changes that rocks undergo. It will also be seen that the various changes of temperature as well as the absolute temperatures are of great consequence. Moreover, the heat and light of the sun exert a very important indirect influence upon metamorphism by reason of their being the sole source of the energy which produces plants and animals, and these agents will be seen to have a far-reaching effect upon the alterations of rocks. The effects of the heat and light derived from the sun are fully considered in Chapters VI, VII, and VIII, on "The belt of weathering," "The belt of cementation," and "The zone of anamorphism."

HEAT DERIVED FROM WITHIN THE EARTH BY CONDUCTION OR CONVECTION THROUGH WATER OR MAGMA.

The amount of heat derived by the crust of the earth from the interior depends upon the conductivity of the various rocks and upon the convectional movements of magma and water.

The heat conductivity of the majority of rocks is between 0.4 and 0.6, silver having a conductivity of 100. It is apparent that the conductivity of rocks is very low as compared with that of the metals, but it can not be doubted that there is a steady but slow flow of heat by conduction from the interior of the earth to the zone of observation.

The amount of heat derived by the crust of the earth from intrusions of igneous rocks is very great. So far as this heat passes into the adjacent

rocks by conduction, the coefficients are the same as in the transfer of heat from the interior of the earth. The transfer of the heat of magma to adjacent rocks is probably largely accomplished by convection. The magmas frequently furnish heated solutions. Ordinary circulating waters approach or come in contact with the igneous rocks; they thus become heated. The heated waters move through the rocks controlled by the laws of underground circulating waters (see pp. 146–153), and give up a part of their heat to the surrounding rocks. The important metamorphosing effects of the great igneous masses through water convection may extend several miles. Contact metamorphism is sometimes restricted to the very marked effects due to high temperature immediately adjacent to the igneous rock. However, the alterations thus produced by high temperature as the result of direct conduction are probably small, compared with the widespread effects resulting from the dispersal of heat and material by means of underground waters.

MECHANICAL ACTION AS A SOURCE OF HEAT.

It is a well-known principle that when work is done involving strain of solids within the elastic limit, or subdivision of solids, or differential movement between solids in contact, the energy is partly transformed to heat. Hence strain within the elastic limit, subdivision of the rocks, and differential movement between rock masses and particles and within the particles raise the temperature of the rocks, and this greatly increases the speed and extent of the chemical reactions. Heat developed by mechanical action is therefore an important factor in the metamorphism of rocks. Indeed, the resultant metamorphic products are very different under conditions of movement and under conditions of quiescence; but heat is only one of the factors entering into the differences. (See pp. 685–707.)

CHEMICAL ACTION AS A SOURCE OF HEAT.

Chemical action always produces a positive or negative heat effect, and thus promotes or retards metamorphism.

EFFECTS OF HEAT AND LIGHT ON ALTERATIONS OF ROCKS.

The relations between metamorphism and heat and light may be generally stated as follows: The kinetic energy of the molecules of substances, whether in the form of gas, liquid, or solid, is increased by heat and light.

The speed of metamorphism is therefore largely dependent upon the amount of heat and light present, especially the former.

In rock alteration heat and light produce direct effects and indirect effects.

DIRECT EFFECTS OF HEAT AND LIGHT.

The more important direct effects may be either mechanical or chemical.

Mechanical effects.—The mechanical effects are desiccation, baking, and fusion. At the surface of the earth the heat of the sun frequently results in evaporating the moisture and desiccating the rocks; an attendant result is induration. This process is especially important in the clay sediments, and occurs to the greatest extent in the hot and arid regions, although desiccation is not unimportant in the colder regions. The details of the process especially concern the belt of weathering and are treated in the chapter on that subject. (See Chapter VI, pp. 541–550.) Where igneous rocks as a consequence of volcanism are brought into contact with other rocks the latter may be baked for a longer or shorter distance from the igneous rocks. The process of baking as here used is restricted to modifications similar to those which take place in the baking of bricks; that is, to effects which are mainly due directly to the heat. This process is restricted to the belt above the level of underground water—the belt of weathering—and is therefore treated in detail in the chapter on that subject. (See Chapter VI, pp. 488–494.) Below the belt of weathering the rocks are saturated with water and the heat effects are mainly produced through that agent. Even in the belt of weathering the baking effect is not wholly due to heat, but is partly accomplished through the agency of the contained water, precisely as is the transformation of clay to brick by burning; for all rocks under natural conditions contain gas and water, and usually considerable quantities. During the baking process the original molecules are brought nearer together, but there are also important chemical changes.

Where the masses of the igneous rocks are very great, and especially where adjacent rocks are included in masses of igneous rocks, the rocks may be softened by the heat or even absorbed by the magma. Where the rocks are softened they are likely to be very greatly changed, perhaps recrystallized. Where they are absorbed by the magma they are lost as original rocks and become a part of the magma by which they are absorbed.

When the modified magma crystallizes it takes the form of an ordinary igneous rock, and may show no evidence of the fact that previously solidified rocks have contributed material.

Chemical effects.—In proportion as the temperature is high chemical reactions are likely to take place between solids. This is illustrated by the case-hardening of iron. When soft iron is placed in contact with pulverized charcoal and the temperature is raised to a red heat, but not to the point of fusion, some of the carbon unites with the iron, transforming the outer part of it into steel. Thus it is casehardened. Just how the union takes place between the iron and the carbon is uncertain. It is supposed to be due to the direct union of the solids, but we can not be quite sure that the result is not accomplished through the agency of a gas. The carbon may be partly oxidized, and thus be transformed to the gas carbon monoxide. This may penetrate the iron, which may reduce the carbon monoxide to carbon again. The reduced carbon may at the instant of reduction unite with the iron, forming the carbide, or steel. While it is certain that high temperature is favorable to the mutual chemical reactions of solids, when the temperature becomes so high as to transform the solids to liquids the chemical reactions are those of liquids rather than those of solids.

INDIRECT EFFECTS OF HEAT AND LIGHT.

The indirect effects of heat and light are accomplished through the agents of metamorphism—gases, water, and organic forms. The movements of the atmosphere and hydrosphere are the conjoint effect of heat and light and gravity. It has already been noted that the movements of these bodies are the agents which do the main work of epigene transfer of material. Not only do gas and water act as agents of transfer, but they act as agents for chemical changes. It has already been seen that chemical action may be a direct result of heat. However this may be, it is certain that by far the more important, indeed the dominant, effects which heat and light have upon chemical reactions are accomplished through the agency of gases and water and organic forms. Of the forces heat and light, the former is the important one in the reactions accomplished through the agency of gases and water solutions; but light is very important in the production of organic agencies. The indirect effects of heat and light and all other conjoint forces are considered in connection with the agents of alteration in Chapter III.

GENERAL STATEMENTS.

From the foregoing it is apparent that the effects of chemical energy, gravity, and heat and light are not independent of one another; on the contrary, they are most intricately interlocked. To a considerable degree any one of the forms of energy may be transformed into the others. Consequently the action of one almost always produces an effect upon the action of the others. Moreover, one almost never acts without the action of the others. Frequently all of the forces of metamorphism are important simultaneous factors in the results; again, one or two of the forces may be prominent, or even dominant, the others playing a subordinate part. But, in every transformation of metamorphism, if all the energy factors of the entire system affected be taken into account, some of the energy is changed into the lowest form of energy, heat, and at least a portion of this heat is dissipated.[a]

[a] Daniell, Alfred, A text-book of the principles of physics, 3d ed., Macmillan Co., New York, 1895, p. 51.

CHAPTER III.

THE AGENTS OF METAMORPHISM.

GENERAL STATEMENT.

The agents through which the alterations of rocks take place are gaseous and liquid solutions and organisms. Solutions are the special subject of this chapter. Organisms are influential only in the belt of weathering, and their action is therefore considered in connection with that belt. (See Chapter VI.)

The circulation and work of solutions involve a consideration of the circulation and work of the gases of the earth, of which the atmosphere is the dominant portion, and a consideration of the circulation and work of the water of the earth, of which the ocean is the dominant portion. While the circulation and work of the atmosphere and of overground water may from a purely theoretical point of view be considered as a part of a treatise on metamorphism, the work of these epigene agents is the subject of that division of geology which has been named physiography, and as the work of the atmosphere and overground water is so fully dealt with in connection with that subject, this branch of metamorphism will not be discussed here at all. But the circulation and work of underground gas and water solutions are of fundamental importance in metamorphism and must be somewhat fully considered.

Gas and water below the surface in the openings of the rocks will be called ground gas and ground water, to discriminate them from gas and water above the lithosphere.

Solutions "are homogeneous mixtures which can not be separated into their constituent parts by mechanical means."[a] The properties of solutions vary continuously and regularly with the concentration.[b] Under the

[a] Ostwald, W., Solutions, translated by M. M. Pattison Muir; Longmans, Green & Co., London, 1891, p. 1.

[b] Cameron, F. K., Application of the theory of solutions to the study of soils: Rept. No. 64, Field Operations of the Division of Soils, 1899, U. S. Dept. of Agric., 1900, pp. 142–143.

definition, solutions may be made by mingling gases and gases, gases and liquids, gases and solids, liquids and liquids, liquids and solids, and solids and solids. The solutions resulting from these various combinations may be gases, liquids, or solids, or partly two or all. Gaseous solutions may be formed by the mingling of gases and gases, of gases and liquids, and of gases and solids.[a] Liquid solutions may be formed by the mingling of gases and gases, of gases and liquids, of liquids and liquids, of solids and liquids, and of gases, liquids, and solids. Solid solutions may be formed by the mingling of gases and solids, of liquids and solids, of solids and solids, and of gases, liquids, and solids. But however complex the origin and however numerous the components, the compounds with which the geologist has to deal are gases, liquids, and solids. The two common combinations which he has to consider are gaseous solutions and solids, and liquid solutions and solids. The liquid solutions are universally aqueous. The solids are the rocks. The combinations gaseous solutions and solids, and aqueous solutions and solids will be treated under Parts I and II of this chapter.

PART I. GASEOUS SOLUTIONS.

Since the geological work of gases and vapors can not be practically discriminated, the term gas is here used to cover both gases and vapors.

The gases which are important in rock alteration are oxygen (O_2), sulphur (S_8 to S_2), water gas (H_2O), ammonia (NH_3), carbon dioxide (CO_2), sulphurous oxide (SO_2), boric acid (H_3BO_3), hydrochloric acid (HCl), and hydrofluoric acid (HF).

Never is one of these chemical compounds at work alone upon the rocks; at the place of action there are always solutions of several gases. Mineralizers in rocks, according to the original definition, are substances which act in the gaseous condition;[b] but it will be seen (pp. 490–494) that the term has been practically restricted to peculiar gases under special circumstances. Notwithstanding the definition of the term, the action of water solutions containing certain compounds, which if alone would be gaseous, has been spoken of as due to mineralizers. The term mineralizers, if it is to serve any useful purpose, should be definitely restricted

[a] Daniell, Alfred, A text-book of the principles of physics. 3d ed., Macmillan Co., New York, 1895, p. 330.

[b] Expression "Agents minéralisateurs" first used by Élie de Beaumont and defined by H. Ste.-Claire Deville: Comptes rendus des Séances de l'Académie des Sciences, vol. 52, 1861, pp. 920, 1264.

to the action of some particular compound or compounds, or else to some form of compound, such as gases.

Gaseous solutions require consideration from two points of view—the chemical and physical principles controlling the action of gases and the geological work of gases.

SECTION 1. CHEMICAL AND PHYSICAL PRINCIPLES CONTROLLING THE ACTION OF GASES.

The chemical and physical principles controlling the work of gases may be considered under (1) the gases present, (2) the pressure, and (3) the temperature.

Gases present.—The law of greatest importance controlling the chemical action of gaseous solutions is: The properties of a homogeneous mixture or solution of various gases are the sum of the properties of the constituents of the mixture. To illustrate, when carbon dioxide (CO_2) and oxygen (O_2) are mixed the properties and activities of each are the same as if the same quantity of each were free from the other and occupied the same space. Therefore, in the belt of weathering, where gases are active, the carbon dioxide and oxygen are both doing their work, the one that of carbonation (see pp. 473–480), the other that of oxidation (see pp. 461–473), as if the other were not present. It is clear, therefore, that the properties of gaseous mixtures are additive.

Slight deviations from this law have been noted under certain conditions, but these mainly concern the exact physics of the gaseous solutions rather than their geological work, and hence are not here considered. In applying the law, however, we must be sure that the gases do not unite chemically and produce a new compound. To illustrate, while the law is certainly applicable to the case mentioned, that of a mixture of carbon dioxide and oxygen, it is not certain that this is the case when water gas (H_2O) and carbon dioxide or sulphurous oxide (SO_2) are mixed, for these compounds may unite with water gas, producing carbonic acid (H_2CO_3) and sulphurous acid (H_2SO_3) gases. Certainly the law will not apply to a mixture of the gases ammonia (NH_3) and water, for these gases will largely unite and produce ammonium hydroxide (NH_4OH), which may exist in the form of gas. In case a gas be formed by the union of two or more gases,

the law controlling the action of gases is applicable to the new compound, and to the other gases with which it is mingled but does not unite chemically.

As to the relative importance of the gases, it might at first be thought that the strong acids, such as hydrochloric and hydrofluoric, are of greater consequence than the much less active compounds, carbon dioxide and oxygen; but it should be remembered that carbon dioxide and oxygen are everywhere at work upon the surface of the earth, whereas the presence of the strongly active compounds in more than minute quantities is exceptional. It therefore follows that the action of the universally present weaker agents, such as carbon dioxide and oxygen, is of immeasurably greater geological importance than the action of the stronger but much less abundant gases.

The pressure.—Increase of pressure increases the chemical activity of a gas. This law follows from the fact that the number of molecules which act upon a given space is directly as the pressure. The varying atmospheric pressure may be taken as illustrating this principle. When the pressure increases, say, by .05, this means that 1.05 times as many molecules of gas are actively at work upon a given area as before.

One of the best illustrations of the increased activity of gases in accomplishing chemical work when under pressure is that of carbon dioxide. As shown in another place (pp. 175–176), carbon dioxide is capable of decomposing many silicates at ordinary temperatures; but Struve and Mueller[a] have shown that when carbon dioxide is under pressure its effect in decomposing silicates is very much greater than under ordinary conditions. This is in accordance with the law of mass action. In proportion as the pressure increases the number of active molecules increases, and therefore the geological work increases in proportion.

The temperature.—The activity of gases increases with increase of temperature. In proportion as the temperature is high, the kinetic molar energy of the molecules of gases is great. The absolute temperature of a perfect gas is believed to be a direct measure of its kinetic molar energy. By molar kinetic energy is meant the energy of translation of the molecule of a gas, and not the vibratory or rotary motions of the molecules themselves.

[a] Mueller, Richard, Untersuchungen über die Einwirkung des kohlensäurehaltigen Wassers auf einige Mineralien und Gesteine: Tschermaks mineral. Mittheil., vol. 7, 1877, p. 47.

The kinetic energy of a moving body is the product of one-half of its mass into the square of its velocity. When a gas is very dense its molecules are closely crowded, and on account of the molecular attraction there is an appreciable decrease in the theoretical pressure, which is a measure of the kinetic molar energy. Since the kinetic energy of the gaseous molecular projectiles increases as the squares of the velocities, this may explain why a slight increase of temperature often greatly increases the chemical reactions of the gases in contact with the solids of the earth's crust, for the likelihood of a chemical union depends, among other things, upon the energy with which the particles of a gas come in contact with the minerals of the rocks.

SECTION 2. GEOLOGICAL WORK OF GASES.

The observable geological work of gases is mainly above the level of ground water, or in the belt of weathering. In the belt of cementation, below the level of underground water, the rocks are saturated with water solutions. Gaseous substances, if present, would be in solution in water, and their action would therefore fall under water solutions, treated on later pages.

In the belt of weathering oxygen and carbon dioxide are immeasurably the most important of the mineralizers, because they are present in the interstices of the rocks in this belt throughout the land areas. However, in volcanic districts any or all of the geologically important gases may be present and have a very marked metamorphosing effect upon the rocks. But of these gases that of water is of vastly the greatest consequence. The consideration in detail of the effects of these various mineralizers and of their action in conjunction with other agents properly falls in Chapter VI on "The belt of weathering."

In the deep-seated zone of anamorphism water itself is mainly above its critical temperature (see pp. 659–661), and is therefore in the form of a gas. On account of the great pressure the gases are dense. Under these conditions most or all of the substances held in solution would also be in the form of gases. The active substances would be solutions of gases in gases. One would expect that the action of water gas holding in solution other gases under such conditions of pressure and temperature would be different from the action of highly heated water, in that its viscosity would

be very small. It would therefore have a greater penetrating power than water, and would be more highly energetic in its action. Under these conditions the minutest spaces would be somewhat readily traversed. The rocks of the deep zone in which action of this kind has taken place can reach the surface only by passing through the zone in which water is in the liquid form. Therefore the effects which were produced by the mineralizers in the deepest zone will have been modified by the action of water solutions during the long time the rocks were in the belt of cementation. The details of the effect of water gases in the zone of rock flowage will be considered in Chapter VIII, on "The zone of anamorphism."

All of the gases may act in either of two ways: (1) By their presence they may influence crystallization or recrystallization without entering into combination. (2) They may enter into the combinations forming oxides, hydroxides, carbonates, sulphates, etc. The first of these actions is spoken of as that of crystallizers, and the second as that of mineralizers. In the metamorphic rocks it is ordinarily difficult to prove the past action of gases, not in water solutions. Occasionally the materials of volcanic cones have been rendered porous and the rocks altered in consequence of the action of gaseous exhalations. In such cases the gases usually have united to some extent with the materials through which they have passed, and in this way furnish evidence of their past action.

PART II. AQUEOUS SOLUTIONS AND SOLIDS.

GENERAL CONSIDERATIONS.

The one liquid through which the greater part of the alterations of rocks occur is water solution. Indeed, this is so profoundly true that the water of the earth has been compared with the blood of an organism. And it is certainly true that the transformations of tissues by the blood are scarcely more far-reaching than those of the lithosphere by the agency of water. It has been determined by laboratory experiments that pure water at ordinary temperatures is capable of dissolving all compounds to some extent. Corresponding with this fact, analyses of ground waters show that they contain in solution all of the elements which occur in nature. The solutions may vary from very dilute to rather strong. So far as the gases are dissolved in water, their action is to be treated under water solutions, not under gases.

In the belt of weathering, above the free surface of ground water, gaseous solutions and liquid solutions work together. In this belt the rocks are not ordinarily saturated with water, but on the average contain a considerable amount of water held by adhesion between the liquid and the solid mineral particles. It is believed that in this belt the gases act upon the rocks chiefly through water solutions. As evidence of this is the small amount of decomposition of the disintegrated rocks in arid regions. (See pp. 496–498.) It therefore appears that the dominant agents of alterations in the belt of weathering are aqueous solutions.

In the belt of cementation below the free surface of ground water the rocks are practically saturated, and in this belt aqueous solutions are the chief agents of alterations.

Water solutions are also a chief agent in the transportation of material from one place to another.

At this point it is necessary to understand that the places of interaction of aqueous solutions and solids are the contacts between the two. It will be seen later that, on account of the molecular attraction between water and rock, a thin film of water adheres to the solid particles with which it is in contact. This film is not in active circulation, yet it is the part of the agent, water, which is immediately concerned in the transfer of mineral material from the rocks to the solutions and from the solutions to the rocks.

The contact film may take material of the rock into solution. From this film the materials taken into solution migrate to other parts of the solution. Probably the migration from the contact film to the free water is largely by diffusion (see pp. 82–83); but, once beyond the contact film, the migration is largely accomplished by convectional movements. Material may be supplied to the contact film by migration of material from the free parts of the solution. From the contact film material may be deposited in the rocks.

In this connection it is interesting to note that in the portions of the solutions near the contact with solids "there is often a concentration of the dissolved material. This phenomenon has been called adsorption."[a] The phenomena of adsorption seem to show with great clearness, not only that the contact film is the active agent in transfer between the free solu-

[a] Cameron, Frank K., Application of the theory of solutions to the study of soils: Report No. 64, Field Operations of Division of Soils, 1899, U. S. Dept. of Agric., 1900, p. 142.

tions and the solids, but that in this film the migration of the dissolved material is to some extent stayed by the molecular attraction of the crystals.

Aqueous solutions as a geological agent require consideration from two points of view—the chemical and physical principles controlling the action of ground water, and the circulation and geological work of ground water. These are treated in the following sections I and II, respectively:

SECTION I. CHEMICAL AND PHYSICAL PRINCIPLES CONTROLLING THE ACTION OF GROUND WATER.

The work of ground water, like any other work, requires the expenditure of energy. The energy by which the water accomplishes its work is derived from chemical action, heat, and mechanical action.

In order to comprehend the processes of alteration of rocks it will be necessary to summarize the important conclusions of physical chemistry as to solutions and chemical reactions. The principles here contained are mainly taken from the works of Ostwald and Nernst.

Chemical action will be considered under the headings, "Principles of solutions applicable to ground waters," and "Principles of chemical reactions applicable to ground waters."

PRINCIPLES OF SOLUTIONS APPLICABLE TO GROUND WATERS.

While the consideration of the principles of solution logically falls under general chemical action, and, perhaps, ought to be treated as a special case under the general treatment of chemical reactions, it seems advisable, because the subject of solutions is somewhat simple as compared with the interactions of complex chemical compounds, to take up this subject first, after which the general laws controlling chemical reactions will be given.

The water of rocks, whether at ordinary temperatures and pressures or at higher temperatures and pressures, may take any of the substances with which it comes in contact into solution; it may deposit substances from solution; it may combine with substances forming hydroxides, as in the case of many of the zeolites and limonite; it may part with its hydrogen in exchange for bases, thus at the same time changing the composition of the rock and taking the bases replaced into solution. This is illustrated by the alteration of enstatite to talc. (See Chapter V, p. 268.) There may be

reactions as a result of different substances being taken into solution at different times; there may be reactions as a result of different solutions coming together, and thus mingling; there may be reactions between substances in solution and the solid material with which the water is in contact; there may be reactions as a result of changing temperature and pressure. All these changes are in the nature of chemical action. Therefore by chemical action through solutions is meant the taking of material into solution, the deposition of material from solution, the interchange between materials in solutions, the interchange between materials in solutions and adjacent solids, and, finally, the interchange of the adjacent solid particles, for such an interchange is usually accomplished through the medium of a separating film of water. In this case the apparently simple reaction between solids is really accomplished by transfers through separating solutions. In all these interchanges the materials pass through a stage of solution.

Salts are combinations of the metals and the acid radicals. Thus Na_2SO_4 is a combination of Na_2 and SO_4, and $KClO_3$ of K and ClO_3. Faraday called these constituents ions. This term will be used as defined by Faraday without any implication that a compound in solution separates into its constituent ions or is dissociated.

According to many chemists[a] salts in various solutions are at least partly separated into their ions. Such supposed separation has been called electrolytic dissociation. If electrolytic dissociation takes place to a considerable extent, the properties of the compounds are practically the sum of the properties of their separated ions. In its power of dissociation of dissolved salts water is held to exceed all other solvents. Water itself is held to be slightly dissociated, or the H_2O separates into the ions OH and H. According to the theory of dissociation the presence of free ions in water solutions is therefore universal. By the advocates of the theory it is held that it is by the interaction of these free ions that chemical interchanges are accomplished. But dissociation is held to be very imperfect in strong solutions, relatively far advanced in dilute solutions, and in very dilute solutions nearly or quite complete. As the greater portion of

[a] Nernst, W., Theoretical chemistry, trans. by C. S. Palmer, Macmillan & Co., London, 1895, p. 307. Ostwald, W., Outlines of general chemistry, trans. by James Walker, Macmillan & Co., London, 1895, pp. 266–290.

underground solutions are very dilute, at least where somewhat free circulation is the rule, if the theory of dissociation be true we may suppose that the salts held in solution are largely separated into their ions. While the theory of dissociation and the explanation of chemical reactions by interchange of free ions (see pp. 84–85) have a strong foothold in theoretical chemistry, they have never gained universal support; and recently the theory has been strongly attacked by Kahlenberg, who not only holds that the theory is unnecessary to explain chemical reaction, but brings together many facts which appear to controvert it.[a] He has shown, moreover, that instantaneous chemical changes take place in solutions that are the best of insulators.[b]

Until recently it has not been known how the most important of the geological compounds, the silicates, behave when dissolved. However, Kahlenberg and Lincoln[c] have shown that when dilute solutions of silicates are made the silica exists in such solutions in the form of colloidal silicic acid. To illustrate: If a sufficiently dilute solution of sodium silicate be made, but much more concentrated than ordinarily occurs in underground waters, the compound breaks up into NaOH and colloidal silicic acid. From this fact it would not be supposed that the silicic acid is a chemically active compound, and it is not active near the surface of the earth at ordinary temperatures and pressures; but on subsequent pages it will be seen that at considerable depth, where the pressure and temperature are much above the normal, silicic acid is a most active compound.

Before the ionic theory of solutions gained recognition it was customary in the published analyses of underground waters to suppose that the bases and acids of the dissolved materials are united in a definite way. For instance, chlorine was ordinarily considered as united with the potassium, sodium, or calcium. The sulphuric oxide radical SO_4 was supposed to be united with the oxides of potassium, magnesium, calcium, and sodium. The carbon dioxide radical CO_3 was supposed to be united with the oxides of iron, magnesium, sodium, and calcium. The aluminum and silica were

[a] Kahlenberg, L., The theory of electrolytic dissociation as viewed in the light of facts recently ascertained: Bull. Univ. of Wisconsin No. 47, 1901, pp. 299–351; also Jour. Phys. Chem., vol. 5, 1901, pp. 339–392.

[b] Kahlenberg, L., Instantaneous chemical reactions and the theory of electrolytic dissociation: Jour. Phys. Chem., vol. 6, 1902, p. 1.

[c] Kahlenberg, L., and Lincoln, A. T., Solutions of silicates of the alkalies: Jour. Phys. Chem., vol. 2, 1898, pp. 88–90.

usually regarded as oxides, although in some cases the aluminum was treated as united with the chlorine.[a] However, results of recent analyses have ordinarily been given on the basis of ions.[b]

In a solution, under the law of mass action, each of the bases is to be considered as divided between all acids, and under the theory of dissociation there are also present in the solutions the free ions of both the bases and the acids. For example, suppose a strong underground water solution to contain three bases and three acid radicals; as, for instance, the bases sodium, calcium, and magnesium, and the radicals of carbonic, sulphuric, and hydrochloric acid; then the following nine compounds are present, Na_2CO_3, Na_2SO_4, NaCl, $CaCO_3$, $CaSO_4$, $CaCl_2$, $MgCO_3$, $MgSO_4$, $MgCl_2$, and also the six free ions, Na, Ca, Mg, CO_3, SO_4, and Cl, making altogether fifteen separate combinations of the elements. However, under the theory of dissociation, if the solutions be so weak that the substances in solution are wholly ionized the nine compounds first mentioned will not be present. If the dissociation theory be rejected, under the law of mass action in all cases all of the nine compounds will be present, but not the free ions.

Under the principles of solutions it is necessary to consider the cases of (1) the solution of gases in ground waters, (2) the solution of solids in ground waters, and (3) diffusion.

SOLUTION OF GASES IN GROUND WATERS.

The quantity of gases which can be dissolved in underground water depends upon the gases present, the pressure, the temperature, and the solids in solution.

Gases present.—All the natural gases may be dissolved in water or may unite with water. In the latter case the resultant compounds are dissolved. In both cases solutions are formed.

Since below the level of the free surface of underground water it is clear that the gases enter into solution either by absorption or by combination, it follows that the more far-reaching effects of these substances in metamorphism are not as gases, but as aqueous solutions. The gases are

[a] Peale, A. C., Lists and analyses of the mineral springs of the United States: Bull. U. S. Geol. Survey No. 32, 1886, pp. 43, 115, 133.

[b] Clarke, F. W., and Hillebrand, W. F., Analyses of rocks and analytical methods, U. S. Geol. Survey, 1880–1896: Bull. U. S. Geol. Survey No. 148, 1897. Clarke, F. W., Analyses of rocks, laboratory of the U. S. Geol. Survey, 1880–1899: Bull. U. S. Geol. Survey No. 168, 1900.

therefore important factors in the action of ground waters, but they are of course only a small portion of the substances which ground waters carry. The more important of these gases which pass into ground waters are: Oxygen (O_2), carbon dioxide (CO_2), hydrosulphuric acid (H_2S), sulphurous oxide (SO_2), hydrochloric acid (HCl), hydrofluoric acid (HF), boric acid (H_3BO_3), and ammonia (NH_3). Sulphur and boric acid as gases occur mainly in connection with volcanic action. If the above-mentioned or other gases unite with the water the laws below given as to solubility do not hold; thus carbon dioxide unites with water, forming carbonic acid ($CO_2+H_2O=H_2CO_3$); sulphurous oxide unites with water, producing sulphurous acid ($SO_2+H_2O=H_2SO_3$); ammonia unites with water, producing ammonium hydrate ($NH_3+H_2O=NH_4OH$). In some of these cases, for instance, that of ammonia and sulphurous oxide, the water may unite with many times its volume of the gas, with increase of volume; thus water at 0° C. and atmospheric pressure absorbs 1,050 volumes of ammonia as a result of the union of the two. What portion of CO_2 contained in ground water remains as CO_2 in solution, and what part unites with water, forming carbonic acid, is uncertain, but it is definitely known that much of the CO_2 contained in the ground water is in the form of the so-called bicarbonates—for instance, such salts as $Na_2CO_3+H_2CO_3$ or $2NaHCO_3$—and therefore is united with the water.

When new compounds are formed by the union of the gases with the liquids, the substances held in solution are the new compounds. When these new compounds are gases the laws below given concerning the solution of gases in liquids apply only to the new compound, not to the original gas. Where the compound is a solid—as, for instance, a bicarbonate—the laws for the solution of gases in water do not apply, but such compounds are held under the laws controlling the solution of solids in liquids. (See pp. 72–82.)

In some cases in nature a part of a gas may unite with a substance in solution and make a new compound and a part may unite with water and be dissolved in this form. If both the compounds be gases the laws for the solution of gases in liquids hold. If the new compound formed be a solid salt the laws for the solution of solids in liquids apply to it, and the laws for the solution of gases in liquids apply to the uncombined gas. This case is illustrated by carbon dioxide, already mentioned.

The pressure.—"The quantity of a gas dissolved by a specified quantity of a liquid is proportional to the pressure of the gas."[a] This statement is true of each gas without reference to whether a gas be alone or mixed with other gases. Thus the solubility of each of a number of mixed gases is controlled by the pressure exerted by that gas, not by the total pressure exerted by the mixture. It is therefore clear that under natural conditions the pressure of that part of any gas which is in the atmosphere and the pressure of that part which is held in solution in the water immediately adjacent are the same when the two are in equilibrium, and the water is therefore just saturated.

So far as ground waters are concerned, there are two cases; first, the waters of the belt of weathering, or those to the level of ground water; and second, those below the level of ground water, or the belt of saturation. In the belt of weathering the pressure is atmospheric. Changes of pressure are barometric. In so far as the atmospheric pressure varies—and this is by fractions up to one-fifteenth—the solubility of the natural gases in the water of the belt of weathering also varies directly as the pressure of each of the gases varies, without reference to the pressure and solubility of the other gases.

In the belt of saturation, just at the level of ground water, the amount of gases held in solution is proportional to atmospheric pressure; but at greater depths higher degrees of concentration of gases are possible, although it might at first be thought that the atmospheric pressure or vapor pressure at the free surface of the water would determine the concentration of the solution. The pressure which really is determinative as to the amount of gas which may be held in solution is that of a column of water extending to the free surface, plus the atmospheric pressure. Since, however, water is so much heavier than the atmosphere, at considerable depths below the level of ground water the atmospheric pressure may be neglected; and the pressure, and therefore the solubility of underground gases in water, is almost directly proportional to the depth below the level of ground water. For instance, at a depth of only 100 meters below the level of ground water the pressure of the atmosphere is only one-tenth that of the water pressure; at a depth of 1,000 meters it is only one

[a] Ostwald, W., Solutions, translated by M. M. Pattison Muir; Longmans, Green & Co., New York, 1891, p. 9.

one-hundredth, and at still greater depths the fraction of pressure due to the atmosphere is insignificant.

But in order that saturation for any gas corresponding to the pressure at any given depth shall occur, it is necessary that a sufficient amount of gas shall there exist. Gases may be produced below the level of ground water by the chemical reactions, as by the liberation of carbon dioxide in the process of silication. Later it will be seen (see Chapter VIII, pp. 677–679) that this is one of the fundamental processes of the lower physical-chemical zone. It follows from the above that at depth the amount of carbon dioxide or other gas in solution per unit of water may be many score times greater than near the surface. The pressure of carbon dioxide at the surface is only about 0.0006 of an atmosphere. The water pressure at a depth of 1,000 meters is almost 100 atmospheres; therefore the amount of free carbon dioxide which may be held in solution, if pressure were the only factor concerned, might be 166666 times as great as that held in solution in the belt of weathering.

But it must be remembered that, as shown below, the increase of temperature due to increase of depth somewhat reduces this multiple.

It should be remembered also that carbon dioxide combines with water, producing carbonic acid, and the amount of this compound which may be held in solution at the surface of ground water is not dependent upon the pressure of the atmospheric carbon dioxide. But it is evident that deep ground waters, where the pressure is great, may hold a vastly greater quantity of carbon dioxide than can be held in solution near the level of ground water.

As already pointed out, the law which obtains in reference to geological work is that the activity of the carbon dioxide increases in direct ratio with its quantity.

The theoretical conclusion that the action of carbon dioxide would be increased by pressure, and consequent greater quantity, has been experimentally verified by Mueller[a] and Struve, who found that strong pressure increased the action of carbon dioxide in the decomposition of the silicates more than did increase of time.

[a] Mueller, Richard, Untersuchungen über die Einwirkung des kohlensäurehaltigen Wassers auf einige Mineralien und Gesteine: Tschermaks mineral. Mittheil., vol. 7, 1877, p. 47.

The temperature.—Increase of temperature generally results in decrease of solubility of a gas.[a] Increase in temperature with depth, or because of volcanism, lessens the solubility of gases in ground water, and to this extent works against the effect of increased pressure.

Solids in solution.—There is still another factor which enters to a slight extent into the solubility of gases. Water holding solids in solution, in most cases, absorbs less of a gas at a given pressure than does pure water.[b] However, the solutions near the surface are ordinarily so dilute that this law is probably not important, but at depth it may be of some consequence in working against the effect of increased pressure.

SOLUTION OF SOLIDS IN GROUND WATER.

Where a solid is placed in a liquid some or all of it dissolves, and thus forms a homogeneous mixture composed of the two, or a solution.

It has been found that if a liquid be placed in a vessel having two compartments separated by a membrane through which the solvent but not the dissolved substance may pass, when a soluble compound—for instance, sugar—is dissolved in the liquid in one of the compartments, pressure against the membrane is produced. This pressure has been called osmotic pressure, to distinguish it from ordinary gas pressure, known as vapor pressure. According to van't Hoff, the osmotic pressure "is independent of the nature of the solvent, and in general obeys the laws of gases." That is to say, "the osmotic pressure is proportional to the concentration; the osmotic pressure is proportional to the absolute temperature; the same osmotic pressure can be obtained by equimolecular quantities of the most various substances in the same solvent; the osmotic pressure is exactly the same as the gas pressure which would be observed if the solvent were removed and the dissolved substance were left filling the same space in the gaseous state at the same temperature."[c] These somewhat sweeping statements need various modifications. For instance, where the solutions are very concentrated the molecules in solution are believed to be so close to

[a] Ostwald, W., Outlines of general chemistry, translated by James Walker, Macmillan & Co., London, 2d ed., 1895, p. 121.

[b] Ostwald, op. cit., p. 121.

[c] Nernst, W., Theoretical chemistry, translated by C. S. Palmer, Macmillan & Co., London, 1895, pp. 134–137. Ostwald, W., Solutions, translated by M. M. Pattison Muir; Longmans, Green & Co., New York, 1891, pp. 112–117.

one another that molecular attraction produces an effect, and in this case the osmotic pressure does not vary directly as the concentration. But, Cameron says, in so far as the molecules in solution are sufficiently separated so that they may act as a gas, "the volume, pressure, and temperature relations are dependent only upon the number of molecules involved."[a]

Since all of these relations are the same as the laws controlling the behavior of gases, it is held by many physical chemists that when a solid passes into solution it is transformed to a gas. Under this explanation the osmotic pressure is a gaseous pressure. "The kinetic energy of the molecules of the dissolved substance is equal to that of the gas at the same temperature; and, moreover, as the kinetic energies of the molecules of the dissolved subtance and of the solvent must agree, because these molecules are in immediate contact, it follows also that the kinetic energy of the molecules of the liquid must, on the whole, be the same as that of gaseous molecules at the same temperature."[b]

If the above theory be correct, it follows that the solution of solids in liquids is similar to that of gases in liquids; for in both cases the compound when dissolved is in the form of a gas; and the geological work of underground water, whether the solutions be produced by a mingling of gases and water, solids and water, or the three combined, could be considered as a unit. (See pp. 63–64.)

In case a salt dissolved in water be an electrolyte, under the dissociation theory it is separated into ions to some extent. If this be so, the number of dissolved particles is represented by the number of ions plus the number of undissociated molecules. Therefore in very dilute solutions, where the dissociation is held to be complete, the number of dissolved particles and consequently the osmotic pressure is doubled in the case of a salt of a monad acid with a monad base. Thus the law of equal gaseous pressure for equal number of molecules is believed by many to still hold good. For instance, if NaCl dissociates into the ions Na and Cl, or KOH into the ions K and OH, thus giving twice as many molecules as in the case of a compound which does not ionize, under the law the osmotic pressure is twice as great as that of the compound which does not dissociate.

[a] Cameron, F. K., Application of theory of solutions to the study of soils: Report No. 64, Field Operations of Division of Soils, 1899, U. S. Dept. of Agric., 1900, p. 144.

[b] Ostwald, op. cit., p. 148.

The conclusions of van't Hoff, Ostwald, and others in reference to osmotic pressure being due to gaseous pressure of the dissolved substances have never been accepted by Mendeléeff, and have recently been strongly opposed by Kahlenberg. Certainly there are many discrepancies between the observations made as to the amount of osmotic pressure and the amount which the pressure should be under the gas law. But, so far as the observations of geology show, I see nothing that controverts or confirms van't Hoff's theory. In studying the work of underground solutions I have been unable to discover any criteria which will separate the work of gases in water solutions from the work of solids in water solutions. So far as geology is concerned, solutions of gases in water and solutions of solids in water can not be discriminated. It has been held by some that the presence of fluorite and other minerals is evidence of gaseous action, but, as yet, I have not been able to find valid evidence offered by any author for this conjecture. It may be that gases dissolved in water and solids dissolved in water are held in solution in consequence of chemical affinity, as held by Mendeléeff, or they may be in solution as gases, as held by van't Hoff, but in either case the manner of action of the two is the same, and therefore there is no warrant for attributing the development of fluorite, tourmaline, etc., to the presence of "mineralizers" in the sense that these compounds are the products of the action of gases as opposed to water solutions.

When a soluble solid is placed in a liquid solvent it at once begins to dissolve. The temperature and pressure remaining constant, if an excess of the solid be present after a sufficient time there is no further decrease in the amount of the solid present, nor is there any increase. When this state is reached the solution is saturated.

When a solid is in a saturated solution, and therefore constant in amount, even if temperature and pressure remain constant it does not follow that no interchange takes place between the dissolved and solid salt. The kinetic theory of solutions leads to the conclusion that many molecules are released from the solid to the solution, and pass from the solution into the solid, but these amounts balance. This is well illustrated by sugar solutions. If finely pulverized sugar be placed in the bottom of a saturated sugar solution and sugar-covered threads be suspended in the solution, sticks of rock candy will be formed. The crystals of the candy grow at

the expense of the sugar below, which is being constantly taken into solution and deposited as crystals about the string; and, therefore, although the solution is continuously saturated, there is continuous solution and deposition. Even if no sugar-coated strings were placed in the sugar, after a time it would be found to be coarser grained or to have recrystallized. Thus the constant interchange between a saturated solution and that of an adjacent solid is certain.

The change occurs under the law by which large crystals grow at the expense of small ones. In order that crystals shall grow in a solvent, it is necessary that the solutions shall be saturated or supersaturated at the immediate place of crystal growth. Since underground there is always a superabundance of many materials as compared with the amount of water, we may suppose that at a moderate depth below the surface, and especially in the smaller spaces, where movement is very slow (see pp. 138–146), the solutions are often saturated. It is well known that the growth of larger crystals at the expense of smaller ones, under conditions of saturation and superabundance of material, goes on more rapidly in proportion as the temperature is high and the pressure is great. The principle is taken advantage of in the chemical laboratory in the production, before filtration, of a coarse precipitate by boiling or other means. During the process the finer particles of the precipitate are dissolved and the coarser ones are enlarged at their cost. The growth of the large crystals at the expense of the small ones is due to the fact that the smaller crystals are somewhat more soluble than the larger. The explanation of this change, as given by Ostwald,[a] lies in the "surface tension which exists on the boundary surfaces between solids and liquids, as on those between liquids and gases—the so-called free surfaces of liquids. This tension acts so that the surfaces in question are reduced in size, with the consequent enlargement of individual crystals (the total amount of precipitate remaining practically unaltered), i. e., with the coarsening of the grains." During the change, for a given volume of solid the lessening of the total surface of the crystals, and consequently the lessening of the surface tension, results from the fact that the surfaces are small in proportion as the individuals are large. For a given volume of a substance the surfaces of the crystals are inversely as their diameters. (See

[a] Ostwald, W., The scientific foundations of analytical chemistry, translated by George McGowan, Macmillan & Co., London, 1895, p. 22.

p. 98). The increase in the size of the crystals, lessening the surface tension, may be considered as a transfer of potential into kinetic energy. This passes into heat and is dispersed under the apparently general law of the dissipation of energy. Why the tendency to the transformation of all forms of energy into heat and the dissipation of heat should be a law of nature it is not my purpose here to discuss. But such the law seems to be, and in its application we carry the causal sequence as far as we are now able.

The growth of large individuals at the expense of small ones in ground water is of the most profound significance in the metamorphism of rocks. It is illustrated by the secondary enlargement of minerals and by the porphyritic crystals which frequently develop in schists and gneisses, such as the porphyritic crystals of feldspar, hornblende, garnet, staurolite, etc. (See pp. 643–644, 699–700.)

The above principle in reference to the growth of large crystals at the expense of small ones is very clearly applicable to the growth of segregations of minerals of a certain kind as compared with smaller segregations. If, for instance, at one place there be a mineral aggregate, this, so far as the surface tension and the free surface of liquids are concerned, acts as a unit and tends to draw to itself the material of smaller aggregates or of individual mineral particles. For aggregates which do not have crystal boundaries the form which would be assumed under ideal conditions is spherical. This principle of the growth of large aggregates at the expense of small ones is illustrated by chert nodules. (See pp. 816–818.)

The quantity of a solid which can be dissolved in aqueous solutions depends upon the compounds present, the pressure, and the temperature. When the limit of solubility is reached the solution is said to be saturated.

COMPOUNDS PRESENT.

Theoretically all compounds are soluble to some extent in water. This statement applies to all natural compounds; that is, the minerals of nature are elements, oxides, or salts which are soluble in water. No substance is wholly insoluble in the ground solutions, even at the ordinary temperatures and pressures. This statement is illustrated by the solution of quartz and the more refractory silicates at the surface.[a] Under surface conditions

[a] Hayes, C. W., Solution of silica under atmospheric conditions: Bull. Geol. Soc. America, vol. 8, 1897, pp. 214–217.

quartz grains are sometimes etched by meteoric waters, and the decomposition and partial solution of the refractory silicates is universal. Under conditions of deep-water circulation solution of quartz and the refractory silicates may be accomplished with relative rapidity. This is illustrated by the Calumet and Hecla conglomerate, many of the pebbles of which have been partly or even completely dissolved and the space once occupied by them taken by copper.[a]

Since underground solutions always contain a number of compounds, and often many, the influence of one compound upon the solubility of another is of consequence in various ways. For instance, when several compounds are present, a unit quantity of water will not dissolve as much of a given salt as it would if it were alone. But if a number of units of water are each saturated with a single salt, and the solutions are mingled without chemical reaction, the mixture is capable of taking additional quantities of the salts into solution. In other words, a unit of solution simultaneously saturated with each of several compounds contains a greater total of solids than a unit of solution saturated with fewer of these compounds, but less of any individual salt than it would were it saturated with that salt alone.[b]

In the ground solutions the different compounds frequently react upon one another, and therefore important modifications in the above statement are necessary, as is explained under "Precipitation," pp. 113–123.

RELATIONS OF SOLUTION AND PRESSURE.

In general, the volume of the solvent plus that of the dissolved compound is greater than that of the solution. For a given quantity of the solid the contraction is greater the more of the solvent is used.[c] In some cases, however, the volume of the dissolved compound and solvent is less than that of the solution, or expansion results from dissolving the solid. Ammonium chloride in water is an illustration of this case. From the foregoing relations we obtain a rule as to the relations of pressure to solubility.[d] In the common case in which the volume of the solution is less than that of

[a] Pumpelly, R., The paragenesis and derivation of copper and its associates on Lake Superior: Am. Jour. Sci., 3d ser., vol. 2, 1871, p. 34.

[b] Ostwald, W., Solutions, translated by M. M. Pattison Muir; Longmans, Green & Co., New York, 1891, pp. 83, 84.

[c] Ostwald, W., op. cit., p. 82.

[d] Nernst, W., Theoretical chemistry, translated by C. S. Palmer, Macmillan & Co., London, 1895, p. 567.

solvent and solid, pressure increases solubility; for in that case solution tends to bring the molecules nearer together and works in conjunction with the pressure. A mixture of water and ice furnishes an excellent illustration of this principle. At any moment the volume of the water is less than that of the equivalent water and ice. Hence pressure promotes solution and prevents freezing, or in other words, crystallization. In the reverse case, that in which the volume of the solution is greater than that of solvent and solid, pressure decreases the solubility, the reason being the reverse of that of the previous case.

The above law may be illustrated by fig. 1. A given amount of salt, say 10 cc. in volume, may be supposed to be placed in 90 cc. of water, and the salt be of such a nature as to saturate the water at that temperature and pressure. Before solution begins the space occupied is 100 cc. After solution this space may be greater or less than 100 cc., say 105 cc. or 95 cc.; that is, the water surface instead of being at *aa* will be at *cc* or *bb*. If it be at *bb*, where the volume is less, and the pressure be increased, an additional amount of salt may be added and taken into solution. If it be at *cc*, and the pressure be increased, a part of the salt already in solution will be precipitated from the solution.

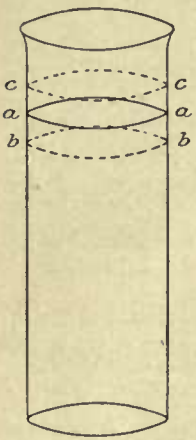

FIG. 1.—Change of volume resulting from solution, and relations of solution and pressure.

It is well known that the solubility of calcium carbonate and of some other carbonates is increased by pressure.[a] It is a fair inference from Barus's work that the solubility of the silicates is also increased by pressure. Barus[b] found that when soft glass is dissolved in water at temperatures above 210° C., the volume is 20 to 30 per cent less than the two separately. This glass is one which contains alkalies, alkaline earths, and lead, and therefore is somewhat similar in composition to many natural silicates. The carbonates and the silicates are the dominant compounds in underground solutions. The solubility of many other salts, besides the carbonates and silicates, occurring underground is increased by pressure. Therefore, in the majority of the complex underground solutions

[a] Lindgren, W., Gold-quartz veins of Nevada City and Grass Valley, California: Seventeenth Ann. Rept. U. S. Geol. Survey, pt. 2, 1896, pp. 176–178.

[b] Barus, C., Hot water and soft glass in their thermodynamic relations: Am. Jour. Sci., 4th ser., vol. 9, 1900, p. 173.

the totals of the salts in solution are in general increased by pressure, and the volumes of the solution are less than those of the salts and solvents separately.

RELATIONS OF SOLUTION AND TEMPERATURE.

The relations of solution and temperature have three phases; first, the speed of solution; second, the quantity of material which may be held in solution; third, the relations of solution to absorption and liberation of heat.

Speed of solution.—The speed of solution is commonly increased greatly by rise of temperature.[a] A slight increase in temperature may increase the rate of solution out of all proportion to the absolute change in temperature. At temperatures above 100° C., and especially above 185° C., the activity of water may increase to an amazing degree. The rapid solution of glass, by Barus,[b] at temperatures about 185° C. illustrates this. At any temperature solution will continue until the point of saturation is reached, but this state will be attained at high temperatures in but a small fraction of the time required at low temperatures. For instance, to saturate an underground solution with the refractory silicates or sulphides at ordinary temperatures might require months, or even years, while to saturate them at temperatures above 185° C. might require only an equal number of minutes, or at most, hours. The capacity of water for action at high temperatures combined with pressure, considered above, is adequate to explain the complete recrystallization of great volumes of rock. (See pp. 749–751.)

Quantity of material which may be held in solution.—The effect of temperature upon the quantity of material which may be held in solution does not admit of a simple general statement.[c] For most substances moderate increase of temperature gives greater capacity for solution; but for many substances there exists a temperature at which there is the maximum capacity for solution, and the amount of material which may be held in solution at higher and lower temperatures is less than this maximum. The quantitative relations of solution and temperature at ordinary pressure between

[a] Nernst, W., Theoretical chemistry, translated by C. S. Palmer, Macmillan & Co., London, 1895, p. 568.

[b] Barus, C., Hot water and soft glass in their thermodynamic relations: Am. Jour. Sci., 4th ser., vol. 6, 1898, p. 270, and vol. 9, 1900, pp. 167–168.

[c] Ostwald, W., Solutions, translated by M. M. Pattison Muir; Longmans, Green & Co., New York, 1891, pp. 55–77.

0° C. and 100° C. are shown by fig. 2, taken from Ostwald.[a] For various substances the maximum capacity for solution lies between 60° and 140° C., and for many substances it is probably below 200° C. It therefore follows, in respect to underground solutions, that a general statement can not be made as to how change of temperature may affect solubility. However, it is highly probable that up to temperatures of 100° C., and therefore under normal conditions to depths of 3,300 meters, increase of temperature increases the average capacity of underground water to hold material in solution; and it is probable that the average capacity of ground water increases to temperatures considerably above 100° C., and therefore to depths greater than 3,300 meters. But when water passes downward to the deeper parts of the zone of fracture the increase in temperature may lessen the average capacity for holding material in solution, provided the joint effect of pressure be barred. But it has been seen that increasing pressure with increasing depth promotes solubility. It is almost certain that high temperature and pressure combined greatly increase the capacity of water for solution. This is proved by the experiments of Barus upon the solubility of glass. He has shown that at temperatures above 185° C. and below 200° C it is possible "to impregnate glass with water to such an extent as to make it fusible below 200° C. The solution occurs with contraction of bulk relatively to the ingredients and increasing compressibility." . . . "If these solutions are sufficiently concentrated they coagulate at ordinary temperature and the congealed aqueous glass is not different in general appearance from common glass. The melting point of the coagulated aqueous silicate frequently lies below 200° C., probably above 150° C., depending on the glass." And he concludes that "Glass as a colloid is miscible in all proportions with water."[b]

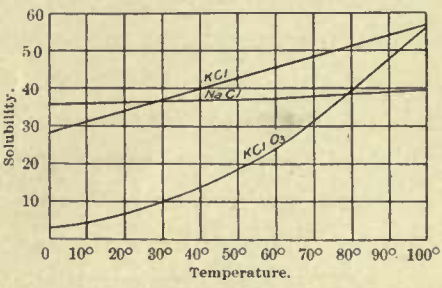

FIG. 2.—Quantitative relations between solution and temperature. After Ostwald.

Since glass is one of the important silicate rocks which occur in nature, these statements are directly applicable to one set of rocks. They may

[a] Ostwald, W., Grundlinien der anorganischen Chemie, Engelmann, Leipzig, 1900, p. 222.

[b] Barus, C., Remarks on colloidal glass: Am. Jour. Sci., 4th ser., vol. 6, 1898, p. 270. See also Am. Jour. Sci., 4th ser., vol. 9, 1900, pp. 161–175.

not be applicable to the same extent to crystallized silicate rocks, but it seems to me highly probable that they apply in large measure to many. In so far as Barus's final conclusion is applicable, there may result all gradations, from solutions in which the water is the dominant constituent to those in which it is the subordinate constituent. This principle of the increased quantity of material which may be held in solution as a result of combined high pressure and temperature is believed to possess very great significance in alterations in the zone of anamorphism, and to be of importance in alterations in the belt of cementation. (See pp. 602–603, 659–661.)

Relations of solution to absorption and liberation of heat.—As already explained, when material passes into solution the molecules are separated and acquire kinetic energy, and are believed by many to change from the solid to the gaseous form. This process absorbs heat. On the other hand, where the volume of the solution is less than the volume of the solvent and salt separately, the molecules of the solvent and salt combined are brought closer together and heat is therefore liberated. In the reverse case, where the volume of the solution is greater than that of the solvent and salt separately, the molecules are pushed farther apart, and heat is absorbed. If the compounds in solution separate into ions this process is believed to be usually attended by liberation of heat.[a] Whether there is a rise or fall of temperature of the solution will depend upon the relative values of these factors. In the common case where there is decrease in the volume as a result of solution, the heat thus liberated by change in volume plus the supposed heat of ionization are together preponderant, and there is, therefore, liberation of heat and a rise in temperature. However, in the case where there is increase in the volume as a result of solution, the heat thus absorbed and the heat absorbed in changing the salt from the state of a solid to that of a gas is greater than that supposed to be liberated by dissociation. The first two factors are dominant, and there is usually a marked absorption of heat and, consequently, a fall in the temperature of the solution. This is illustrated by the solution of ammonium chloride in water. The volume is considerably decreased and the fall in temperature is very decided.

[a] Nernst, W., Theoretical chemistry, translated by C. S. Palmer, Macmillan & Co., London, 1895, p. 562.

DIFFUSION.

It has been seen that the molecules of gases and of solids when dissolved in water are distributed through the solution. When the material dissolved is not evenly distributed the molecules are more abundant here and less abundant there. If the theory be true that the dissolved solids are gaseous the molecules would exert a greater pressure where more closely packed. Under these conditions molecules where more closely packed move toward places where they are less closely packed. This movement is regarded by many as the explanation of osmotic pressure. Kahlenberg, however, does not accept this explanation, but regards osmotic pressure as due to the "mutual attraction between solvent and dissolved substance."[a] Without reference to either theory the more important conclusions in reference to diffusion may be summarized.

The force which drives the dissolved substances from place to place, and the velocity with which a dissolved substance wanders in a solvent, is proportional to the degree of concentration.[b] Therefore, "the quantity of a salt which diffuses through a given area is proportional to the difference between the concentrations of two areas infinitely near one another."[c] In other words, diffusion is proportional to the difference in strength. The quantity diffused is proportional to the square root of the time of diffusion, and the distance over which a determinate concentration extends is also proportional to the square root of the time of diffusion.[d] Several salts in a solution diffuse almost independently of one another, each at its own specific rate.[e] At 20°, according to Ostwald, there is twice as much diffusion as at 0°, and at 40° twice as much as at 20°.[f] When a solution is in equilibrium the concentration of the solution varies inversely as the temperature. It follows that when the temperature of the solution varies, equilibrium is obtained not by equal distribution of the solutes, but by unequal distribution. If the temperature be the same throughout a solution with equal

[a] Kahlenberg, Louis, The theory of electrolytic dissociation as viewed in the light of facts recently ascertained: Bull. Univ. of Wisconsin No. 47, 1901, p. 349.

[b] Nernst, W., Theoretical chemistry, translated by C. S. Palmer, Macmillan & Co., London, 1895, pp. 143–144.

[c] Ostwald, W., Solutions, translated by M. M. Pattison Muir; Longmans, Green & Co., New York, 1891, p. 120.

[d] Solutions, cit., p. 135.

[e] Solutions, cit., p. 139.

[f] Solutions, cit., p. 136.

distribution of the dissolved compounds, a deviation from uniformity in the temperature of the solution will disturb the equilibrium and result in unequal distribution of the dissolved substances.[a]

The values of the coefficient of diffusion (D) of certain substances in water solutions at various temperatures are given by the following table from Nernst:[b] (The table gives the number of grams of the dissolved substance which will pass in one day through a section of 1 sq. cm. when the difference in concentration of the cross section 1 cm. apart amounts to 1 gram in a cubic centimeter.)

Rates of diffusion of certain substances in water solutions at various temperatures.

	Temp.	D.
Hydrochloric acid	0.0	1.4
Do	11.0	1.84
Nitric acid	9.0	1.75
Sulphuric acid	7.5	1.04
Acetic acid	14.0	.81
Potassium hydroxide	13.5	1.66
Sodium hydroxide	8.0	1.96
Ammonium hydroxide	4.5	1.06
Sodium chloride	6.0	.75
Ammonium chloride	17.5	1.31
Potassium chloride	9.0	.66
Barium chloride	8.0	.65
Potassium nitrate	7.0	.92
Sodium nitrate	13.0	.90
Silver nitrate	7.5	.90
Lead nitrate	12.0	.70
Urea	7.5	.81
Chloral hydrate	9.0	.55
Mannite	10.0	.38

This table shows that diffusion is extremely slow. The slowness with which diffusion occurs is due, according to Nernst, to "the resistant friction experienced by the dissolved substance in its movement through the solvent."[c] This friction is very great, because the molecules themselves are exceedingly small.

Later it will be seen that the process of diffusion is of very considerable importance in the migration of compounds in ground water. (See pp. 636–639.) This is illustrated by the very important process of solution and deposition or recrystallization.

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[a] Ostwald, Solutions, cit., pp. 150–151.

[b] Nernst, W., Theoretical chemistry, translated by C. S. Palmer, Macmillan & Co., London, 1895, p. 144.

[c] Nernst, op. cit., p. 145.

PRINCIPLES OF CHEMICAL REACTIONS APPLICABLE TO GROUND WATERS.

GENERAL STATEMENT.

DEFINITIONS.

Before taking up chemical reactions it is advisable to give a number of elementary definitions.

"Compounds whose aqueous solutions contain the hydrogen ion (H) are termed acids, and those which contain the hydroxyl ion (OH) bases."[a] To illustrate, HCl is an acid; NaOH is a base. When the hydrogen ion united with one or more nonmetallic elements is mingled in solution with the hydroxyl ion united with a metal a double reaction occurs, resulting in the union of the hydrogen ions with the hydroxyl ions, forming water, and the union of the nonmetallic parts of the compound with the metallic parts. This latter union forms a salt. For example—

$$HCl+NaOH=NaCl+H_2O.$$
$$H_2CO_3+2NaOH=Na_2CO_3+2H_2O.$$

The acids and salts which contain only a single nonmetallic element are called binary compounds. The acids and salts which contain two nonmetallic elements are called ternary compounds. For example, HCl is a binary acid; NaCl is a binary salt; H_2CO_3 is a ternary acid; Na_2CO_3 is a ternary salt. Compounds having the composition of acids, bases, and salts may be separated from solution as solids, and of course all of these solids may pass into solution.

Some salts also contain a certain amount of acid, and such salts are called acid salts. For instance—

$$Na_2CO_3+H_2CO_3=2NaHCO_3.$$

The latter compound is acid sodium carbonate. On the other hand, some salts contain some additional base, and such salts are called basic. For example, $Fe_2(SO_4)_3$ may be united with $Fe_2(OH)_6$, producing $mFe_2(SO_4)_3.nFe_2(OH)_6$. This compound is basic ferric sulphate.

DISSOCIATION.

In explaining chemical reactions the theory of dissociation as advocated by Arrhenius, Ostwald, Nernst, and others is followed for the most part.

[a] Ostwald, W., The scientific foundations of analytical chemistry, translated by George McGowan, Macmillan & Co., London, 1895, p. 117.

This theory is firmly placed in the text-books. No opinion is expressed by me as to its correctness. Indeed, I have no right to any opinion on the subject. As already pointed out, this theory has been vigorously opposed by Kahlenberg, but as yet that author has offered no constructive theory to take its place. I therefore follow the theory of the standard text-books so far as necessary to show how it would apply to the work of ground solutions if it prove to be true; but so far as practicable I make the statements in such form that they will be correct even if the theory of free ions and reactions between such ions is finally abandoned.

Under the theory of dissociation the superiority of water as a solvent for chemical interchanges is regarded as largely due to the fact that the dissolved substances are separated into their ions to a greater degree than in any other solvent. To the fact of active reactions in water, whatever their cause, are very largely due the profound changes which occur in rocks through the medium of water solutions.

Under the theory of dissociation water solutions, acids, bases, and salts separate into their ions. For instance, HCl separates into the free ions H and Cl; NaOH separates into the free ions Na and OH; and NaCl into the free ions Na and Cl. However, in solutions the dibasic acids are supposed to separate into free ions somewhat differently from what might be expected. For instance, it might be expected that H_2CO_3 would separate into the free ions H_2 and CO_3, but it is supposed to separate thus:

$$H_2CO_3 = H + HCO_3.$$

Other dibasic acids are thought to dissociate in a similar manner. However, if the dibasic acid be very strong the compound ion may again break up. Thus, H_2SO_4 is thought to first break up into the free ions H and HSO_4, and the latter to break up into the free ions H and SO_4, so that these would be the ions present in the water. But in the case of the weak acid, carbonic, it is thought that the last change does not take place, and that the free ions remain H and HCO_3.

Ostwald regards the absence of the second stage of dissociation as the explanation of the peculiar characteristics of carbonic acid.[a] Since carbonic acid is, next to silica, the most important rock-making acid, the manner in which it breaks up is of great consequence in metamorphism.

[a] Ostwald, W., Grundlinien der anorganischen Chemie, Engelmann, Leipzig, 1900, pp. 276–278, 397–398.

HYDROLYSIS.[a]

Under the theory of dissociation, not only do acids, bases, and salts separate into ions in water solutions, but the water itself is believed to dissociate to a very small extent, according to the equation $H_2O=H+OH$, thus simultaneously forming free hydrogen and hydroxyl. If this be true the hydrogen ions and the hydroxyl ions coexist and water solutions to a small extent contain free acids and free bases at the same time. The excellence of water as an agent for reactions between the substances it holds in solution is held to be partly due to hydrolysis.

When strong bases and acids are in solution the amount of their dissociation is believed to be so much greater than that of water that the dissociation of the latter is of little consequence. But if a very strong base be united with a weak acid the solution will give an alkaline reaction, and this is regarded as showing the presence of free hydroxyl ions or of hydrolysis. For instance, if the strong base, sodium, be united with the weak acid, carbonic, and a water solution be made, it is held that hydrolysis will take place to some extent, thus:

$$Na_2CO_3+H_2O=NaHCO_3+NaOH.$$

It is supposed that $NaHCO_3$ breaks up into the ions Na and HCO_3, and the NaOH into the ions Na and OH. Therefore, in a solution of Na_2CO_3 in water the coexistent ions are thought to be H, HCO_3, Na, and OH. Since the base, NaOH, is stronger than the acid, HCO_3, the separation into the ions is thought to be the explanation of the alkaline reaction.

Cameron has shown that sodium silicate in solution gives an alkaline reaction, and his explanation is that this compound is hydrolized in a manner precisely similar to that of sodium carbonate.[b] Not only do solutions of sodium silicate give alkaline reactions, but Clarke has shown[c] that many natural mineral silicates, when treated with pure water, show an alkaline reaction. The following gave permanent alkaline reactions: Phlogopite, oligoclase, albite, cancrinite, sodalite, analcite, natrolite, pectolite, apophyllite, ægirite. The following gave more or less distinct colorations to the phenolphthalein indicator, but in time faded: Muscovite, lepidolite, ortho-

[a] Ostwald, W., Grundlinien der anorganischen Chemie, Engelmann, Leipzig, 1900, pp. 254–257.

[b] Cameron, F. K., Application of the theory of solutions to the study of soils: Rept. No. 64, Field Operations of the Division of Soils, 1899, U. S. Dept. of Agric., 1900, p. 169.

[c] Clarke, F. W., Alkaline reaction of some natural silicates: Jour. Am. Chem. Soc., vol. 20, 1898, pp. 739–742.

clase, leucite, nephelite, spodumene, scapolite, laumontite, stilbite, chabazite, heulandite, thomsonite.[a] If the theory of dissociation be true, this shows that the silicates are hydrolized, thus:

$$R_2SiO_4+4HOH=2R(OH)_2+H_4SiO_4.$$

However, according to Kahlenberg and Lincoln, the H_4SiO_4 does not dissociate into the radicals H and SiO_4, but forms colloidal silicic acid.[b] Thus this compound is inert and the reaction reverses only to a small extent and under favorable conditions, and the hydrate of the alkali metal gives an alkaline reaction.

In a similar manner hydrolysis is held to occur in water solutions of the strong base sodium with the weak acid hydrosulphuric, thus:

$$Na_2S+H_2O=NaHS+NaOH.$$

Cameron further states that hydrolysis is to be expected in the case of the aluminates and ferrates.[c] When a strong acid is united with a weak base the solution gives an acid reaction, and this is also explained by dissociation, the free acid supposed to result from hydrolysis being stronger than the weak base.[d]

Since the three most abundant acids of nature are silicic, carbonic, and hydrosulphuric, all weak, hydrolysis, if true, is a reaction of fundamental importance in metamorphism.

REACTIONS.

When, after a number of chemical substances are brought together, and especially when they are united by a solvent, interactions between them may occur which after a time appear to cease. When the conditions have become such that there is no increase or decrease in the amount of any one of the chemical compounds, the system is in a condition of chemical equilibrium.[e] When two substances in solution, A and B, react upon each other so as to produce two other substances, C and D, if solutions of C and D are mixed they in turn will react upon each other to

[a] Clarke, cit., pp. 740–741.

[b] Kahlenberg, L., and Lincoln, A. T., Solutions of silicates of the alkalies: Jour. Phys. Chem., vol. 2, 1898, pp. 77–90.

[c] Cameron, cit., p. 169.

[d] Ostwald, Grundlinien, cit., pp. 276–278, 397.

[e] Nernst, W., Theoretical chemistry, translated by C. S. Palmer, Macmillan & Co., London, 1895, pp. 355–356.

produce more or less of the substances A and B.[a] That is, the reaction is reversible to a greater or less degree. To illustrate, if two solutions, one of them containing $MgSO_4$ and the other Na_2CO_3, come together, the ions are Mg, Na, SO_4, and CO_3. A part of the Mg will unite with the CO_3, producing $MgCO_3$, and a part of the Na will unite with the SO_4, producing Na_2SO_4. Vice versa, if solutions of Na_2SO_4 and $MgCO_3$ are mingled in a similar manner, $MgSO_4$ and Na_2CO_3 will be produced. The reversible reaction may be briefly expressed thus:

$$MgSO_4 + Na_2CO_3 \rightleftarrows MgCO_3 + Na_2SO_4.$$

The sign $\rightleftarrows$ means that the equations may be read from left to right or from right to left.

These are the facts: The ions do interchange between compounds whenever a chemical reaction takes place. Just how and why they interchange is another matter, upon which there is not agreement. Under the theory of dissociation the interchange takes place through the medium of the free ions. The free ions of a compound A are held to collide with the free ions of the compound B, and thus produce the compound C and D, and vice versa. Or, in the specific case above given, of $MgSO_4$ and Na_2CO_3, the free Mg ions collide with the free CO_3 ions and produce $MgCO_3$, and the SO_4 ions collide with the Na ions and produce Na_2SO_4. From the $MgCO_3$ and Na_2SO_4, $MgSO_4$ and Na_2CO_3 are reproduced in a similar manner. Whether the theory of chemical reactions through free ions be of any value or not, it seems probable that free ions exist for a moment when the interchange takes place. To illustrate, it seems hardly probable that the Mg is united to the SO_4 and the CO_3 at the same time. If the Mg lets go of the SO_4 to attach itself to the CO_3, for that instant the ion Mg is free. The same is true of each of the other ions, Na, SO_4, and CO_3, at the instant of interchange. Hence the question at issue is the cause of the interchange. Does it take place as the result of contact of free ions produced by dissociation, or does the chemical affinity of the Mg for the CO_3 cause a portion of it to leave the stronger acid radical SO_4 for the weaker acid radical CO_3, etc.? But this is a question for chemists to settle. The problem is stated here because it is one of such fundamental importance in metamorphism.

But whatever the cause, reversible reactions are a certainty, and it will

[a] Nernst, W., Theoretical chemistry, translated by C. S. Palmer, Macmillan & Co., London, 1895, pp. 356–357.

be seen that certain reactions of the zones of katamorphism are reversed in the zone of anamorphism, and vice versa. But it should be remembered that to close the cycle in any case, or, in other words, to make a transformation from left to right and then from right to left, thus completely reversing any reaction, requires the expenditure and dissipation of energy.

The most general law controlling chemical systems is expressed by Le Chatelier as follows: "Every change of one of the factors of an equilibrium occasions a rearrangement of the system in such a direction that the factor in question experiences a change in a sense which is contrasted with the original change." [a]

Nernst remarks that this law reminds one of the principle of action and reaction. Put in another way, it may be said that any chemical change, by the mere fact of its occurrence, sooner or later renders the conditions less favorable for its continuance. To illustrate, if the increase in volume demanded by the reaction becomes too great, this may stay the reaction. For example, if calcium acetate and copper acetate be placed together in a very strong vessel and but little additional space be left, the reaction resulting in the expansion of volume will go on until the pressure becomes so great as to stay the reaction.[b] Also, if in a closed vessel a large amount of calcium carbonate be heated it will give off carbon dioxide. But as the amount of CO_2 increases, and the pressure therefore accumulates, the reaction will be retarded and finally cease. At this stage the CO_2 formed unites with the CaO, producing $CaCO_3$, as fast as $CaCO_3$ decomposes and produces CaO and CO_2.

If the heat as the result of a reaction becomes too great, this will stay the reaction. For instance, at low temperatures CO will completely unite with O, producing CO_2; but if the temperature becomes too high, as a result of the change the reaction will be stayed or cease altogether. A case of much greater geological consequence is that of hydration and dehydration. A comparatively low temperature is favorable to hydration of minerals. However, a very moderate temperature—anything above 110° C.—at ordinary conditions of pressure is likely to stay the reaction of hydration, or even to reverse this process and produce dehydration.

[a] Nernst, W., Theoretical chemistry, translated by C. S. Palmer, Macmillan & Co., London, 1895, p. 567.

[b] Jones, H. C., On the increasing importance of inorganic chemistry: Science, new ser., vol. 8, 1898, p. 930.

Van't Hoff states the general law controlling chemical systems in another way: "A transformation will take place of itself only in case it is in a position to do a positive amount of work. If the amount of work done is negative, the transformation can take place of itself only in the opposite sense. If the work done is zero, it can take place in neither sense."[a]

EQUILIBRIUM.

When the ions of any compound, A, unite with the ions of another compound, B, so as to produce C and D, just as fast as the ions of C unite with the ions of D to produce A and B the conditions are those of equilibrium, or of chemical statics. When either change takes place faster than the other, these are the conditions of chemical reactions, or of chemical kinetics.[b] When the two solutions, A and B, were first mingled, the conditions would be those of chemical kinetics for a time—that is, until a certain amount of C and D had been produced. However, when the amount of C and D is sufficiently great, so that they react upon each other to produce A and B as fast as A and B react to produce C and D, the conditions are those of chemical statics, or equilibrium. But it is plain that this does not mean that chemical activity has ceased or that there is real quiescence. Interchange is taking place all the time; but as this interchange is compensatory, no heat effect is produced, and the total quantity of each of the compounds present remains the same. The equilibrium is therefore really dynamic.

HOMOGENEOUS AND HETEROGENEOUS SYSTEMS.

A chemical system is homogeneous "when it has the same physical and chemical nature at every point." When this is not the case it is heterogeneous.[c] A solution is therefore homogeneous. If a solid substance be also present, the system is heterogeneous. A heterogeneous system consists "in the intimate association of different complexes, each of which is homogeneous in itself, such as solid salts and saturated solutions."[d] Each of these complexes is called a phase of the system. "The condition of equilibrium of a heterogeneous system is independent of the relative quantity by weight

[a] Jones, H. C., On the increasing importance of inorganic chemistry; Science, new series, vol. 8, 1898, p. 930.

[b] Nernst, W., Theoretical chemistry, translated by C. S. Palmer, Macmillan & Co., London, 1895, pp. 358–360.

[c] Nernst, cit., p. 357.

[d] Nernst, cit., p. 391.

in which each phase is present in the system."[a] To illustrate, if an excess of salt be in a solution, so that it is saturated, and an additional amount of salt be added, this does not in the least change the quantity of salt held in a given volume of the solution. Therefore the equilibrium in a saturated solution is independent of the amount of undissolved salt in the solution. It follows that in a heterogeneous system "the condition of equilibrium is independent of the relative mass of each of the phases."[b] A simple case of heterogeneous equilibrium is that between ice and liquid water, or between liquid water and water vapor. "For a definite external pressure there corresponds a definite temperature at which the two systems can exist beside each other; thus ice and water are coexistent at atmospheric pressure at 0° C.; and liquid water and water vapor, at atmospheric pressure and at 100° C. If we change the external pressure, at a temperature which is kept constant, or if we change the temperature, at an external pressure which is kept constant, then the reaction advances"[b] to equilibrium in one direction or the other. "The process is ended as soon as the expansive force of the evaporating or dissolving substance is held in equilibrium by the gas pressure of the vaporized molecules or by the osmotic pressure of the dissolved molecules, respectively."[c]

NATURE AND SPEED OF REACTIONS.

The fundamental principle of chemical dynamics is that chemical action is proportional to the active mass.[d] This is the law of mass action.

The speed of a chemical reaction which occurs under any given conditions depends upon the compounds, the strength of the solutions, the mechanical action, and the heat. Hence each of these features requires consideration.

THE COMPOUNDS.

The reactions depend upon the compounds present, or, in other words, upon the nature of the ions composing them; for the conditions under which two ions, A and B, unite may be different from those under which one of these ions will unite with a third, as A with C, or different from those under which two other ions, C and D, unite. In order that ions shall unite in solution they must meet or come within the limits of molecular attraction of

[a] Nernst, cit., pp. 391–392.

[b] Nernst, cit., p. 393.

[c] Nernst, cit., p. 403.

[d] Ostwald, W., Outlines of general chemistry, translated by James Walker, Macmillan & Co., 2d ed., London, 1895, p. 292.

one another under certain definite conditions which are peculiar to each substance. Therefore not every time such a meeting occurs are compounds formed. The ratio between meeting and union in the case of any two compounds is a constant, which can be compared with the constant of any other two compounds, each pair of which has its constant. This is merely another statement of the old law that different substances have different affinities for one another, and it is well known that the chemical affinities are developed only when the molecules are in immediate contact with one another.

The ions which are present in ground waters in any given case largely depend upon the character of the adjacent rocks. In a limestone region, for instance, the water may quickly take into solution all the calcium and magnesium it can hold, considering the acids present. Under such circumstances the acid ions will be mainly balanced by the calcium and magnesium. The other substances, such as sodium and potassium, perhaps in more readily soluble forms than the calcium and magnesium, will be largely kept from going into solution, or if in solution will be partly thrown down, because these substances are obliged to compete for the acid radicals with the vastly greater number of calcium and magnesium molecules. Is it not possible that the agricultural advantage of having calcium and magnesium abundantly in the soil is largely, or at least partly, due to the fact that the presence of these soluble substances in abundance prevents the solution and washing out of the elements potassium and sodium which the plants need?

Ostwald divides the bases into strong, moderately strong, and weak.[a] The alkalies and alkaline earths, with the exception of magnesium, are strong bases; magnesium is a moderately strong base; iron and aluminum are weak bases—of the two aluminum is the weaker. It follows that, other things being equal, in underground solutions the alkalies and alkaline earths, with the exception of magnesium, largely take possession of the acids. To a less extent this is true of magnesium, and to a still smaller degree of iron and aluminum. Thus we have the partial explanation of the relative solubilities of the bases in the belt of weathering. In this belt the alkalies are dissolved to the greatest extent; next in order comes calcium, then magnesium, and finally iron and aluminum. (See p. 518.)

[a] Ostwald, W., The scientific foundations of analytical chemistry, translated by George McGowan, Macmillan & Co., London, 1895, pp. 55–56.

Ostwald divides the acids into strong, moderately strong, weak, and very weak. The acids H_2SO_4, HCl, and HNO_3, are strong acids. The acids H_2SO_3 and H_3PO_4 are moderately strong. The acids H_2S, H_3BO_3, and H_2CO_3 are weak acids. The acids of silica are very weak.[a]

The strong acids H_2SO_4, HCl, HNO_3, when present in ground solutions, as they sometimes are, of course take possession of the bases in proportion to their quantity. However, in the crust of the earth strong acids are not abundant on the average, although under exceptional conditions, as in volcanic districts, they may be rather plentiful. Also the moderately strong acids H_2SO_3 and H_3PO_4 are not abundant, although phosphoric acid is rather widespread. Of the weak acids H_2S and H_3BO_3 are not plentiful. The two great acids of nature are carbonic and silicic acids, and the major contest in the rocks, so far as the acids are concerned, is between the weak carbonic acid and the very weak silicic acid. These two acids are everywhere very abundant in the rocks. While, therefore, the moderately strong and the strong acids play a relatively important part in proportion to their quantity, one weak and one very weak acid, because of their dominant quantity, under the law of mass action play the greatest part in rock alterations; and in the contest the very weak acid, silicic, holds its own against the weak acid, carbonic, partly because its far greater abundance compensates for its relative weakness. The fact of the formation of carbonates and the simultaneous decomposition of the silicates under surface conditions the world over is well known. (See pp. 163, 473–486.) The partial explanation of the phenomena is the relative abundance of carbonic acid under the conditions in the zone of katamorphism. As shown in another place (see p. 479), the reaction is also one which liberates heat, and this is a favorable factor in the process.

In the zone of anamorphism, where the pressure is great, the reaction of the upper zone is reversed. (See pp. 173–178, 677–679.) The replacement of carbonic by silicic acid results in decrease in volume (see p. 177). Therefore, under the great pressures of the zone of anamorphism, the relative volumes of the original and secondary compounds is a most important, probably dominant, factor in the process. But also it is probable that at the high temperatures and pressures which obtain in the lower zone silicic acid gains strength as compared with carbonic acid.

[a] Foundations, cit., p. 55.

It may under these conditions be a stronger acid than at the surface, and if this were the case the reactions would be partly explained. Bearing in this direction is the experiment of Bischof, who has shown that at 100° C. silicic acid, when present in abundance, may partially replace carbonic acid of carbonates.[a]

Ostwald's explanation of the varying strength of the bases and acids is based on the varying amount of supposed dissociation.

The velocity of a reaction is proportional to the masses of the active components, and according to Ostwald these are the free ions. Therefore the speed depends upon the number of free ions which are acting. But the number of free ions which are present is dependent upon the degree of dissociation, and in this matter different compounds vary greatly. Therefore the degree of electrolytic dissociation of the various bases and acids determines their respective strengths and is "the measure of the reaction capacities of all substances."[b]

From this it follows that an acid or base which is strongly dissociated is stronger than, or, in other words, is able to largely replace, an acid or base which is but slightly dissociated; for the number of free ions of the stronger compound far exceeds that of the weaker. It therefore becomes important, from Ostwald's point of view, to know the comparative strength, or the relative amounts of dissociation, of the abundant bases and acids which occur in the rocks. According to Ostwald the strong bases and strong acids may be largely dissociated; the moderately strong bases and acids under ordinary conditions are dissociated to a much less extent; the weak acids, carbonic, hydrosulphuric, and boric, are usually not dissociated to the extent of 1 per cent; silicic acid under ordinary conditions is scarcely dissociated at all.

STRENGTH OF THE SOLUTIONS.

Saturated and strong solutions are more active than weaker solutions; for the amount of the active compound increases with the concentration, but not in a simple ratio. Weak solutions are relatively more active than strong solutions, and by those who believe in dissociation this is attributed to their nearer approach to complete dissociation; but the greater relative activity of weak solutions never compensates fully for the greater dilution.

[a] Bischof, Gustav, Elements of chemical and physical geology, translated by Paul and Drummond, Harrison & Sons, London, 1854, vol. 1, p. 6.

[b] Nernst, W., Theoretical chemistry, translated by C. S. Palmer, Macmillan & Co., London, 1895, p. 440.

Although, as just seen, strong bases and acids have a great advantage over weak bases and acids, the quantity of an element present is a very important factor in the final result of the action of the solutions on the solids. If a certain element is abundant in the ground solutions, it may to a large extent replace another element in the solids, an element of the solid going into solution at the same time. This may take place to a large extent even if the element in solution is weaker than the one it replaces in the solid. For instance, the relatively weak base, magnesium, when abundant in solutions, is known to replace the stronger base, calcium, on a large scale in calcium carbonate, thus changing limestone to dolomite. In this reaction, while the abundance of magnesium is a very important factor, a number of others enter; and therefore its detailed consideration is given under the process of rock dolomitization. (See pp. 802–808.)

MECHANICAL ACTION.

It has already been seen that no changes in rocks take place without movements of material, small or great, for long or short distances. Even in the case of a mineral passing from one form to an allotropic form, there is movement of the molecules. In short, wherever there is rearrangement of the elements there must be movements.

Mechanical action alone is one of the processes of metamorphism of the utmost importance. (See pp. 46–50.) However, the effect of mechanical action in the promotion of chemical action is even more important than mechanical action alone.

Mechanical action influences chemical action in two general ways—the speed is promoted, and the nature of the reaction is modified.

SPEED OF CHEMICAL ACTION.

The speed of chemical action is promoted directly by the deformation, and indirectly by the heat liberated.

DIRECT DEFORMATION EFFECT.

As already shown (pp. 49–50), mechanical action produces deformation in three different ways—by producing strain without rupture, strain with rupture, and readjustment of the particles

Strain without rupture.—When material is strained without rupture, even if the amount of deformation be slight, a great change in the molecular constitution may be involved. This is well shown by a common experiment

on glass. If a piece of glass, free from stress, be placed under the microscope with crossed nicols, the light is cut off because the glass is isotropic. If, however, the glass be slightly flexed, well within the elastic limit, it immediately becomes anisotropic, and brilliant colors flash out. So far as light is concerned—and this is one of the best agents for giving an insight into the molecular constitution of bodies—the strained glass behaves wholly different from unstrained glass. Evidently when glass is alternately strained and freed from strain it undergoes a profound change in molecular constitution. The greatness of the molecular change in material when strained within the elastic limit is dwelt upon to show that such changes might greatly affect chemical action; and it will be seen below that the facts correspond to this expectation.

Barus has shown[a] in the case of metals strained to the point of rupture that a considerable per cent of the energy expended in straining them is potentialized; in "glass-hard" steel 50 per cent, in brass 40 per cent, in copper 25 per cent. A larger percentage of the energy was potentialized in the earlier stages of strain than in the later stages. By stating that energy is potentialized is meant that the mechanical equivalent in heat of the work done on the metals was only partially developed; the remainder of the energy is stored up in the strained metals. Now, considering a brittle substance which is analogous in physical characters to rocks, Prince Rupert drops, the explosion of a drop when a point is broken shows that a large amount of energy is potentialized, or that the glass is in a high state of strain. The experiments of Barus and the condition of the Rupert drop show that in strained materials energy is probably potentialized. If this be true, must it not be the case that the atoms and molecules of a strained body are in a more than ordinarily favorable condition for chemical action?

Bodies in which energy is potentialized are believed to be in an exceptionally favorable condition for chemical action. For instance, if a strained metal, in which on that account more than the usual amount of energy is stored, be dissolved in an acid, less than the usual amount of chemical energy is expended, for the resultant salts in the solution have the same energy of combination in each case. But in the strained metal work has been done, the equivalent of which has not escaped as heat during strain, and is therefore stored energy. Therefore this energy is available

[a] Barus, C., The mechanism of solid viscosity: Bull. U. S. Geol. Survey No. 94, 1892, pp. 107–108.

to assist the chemical reaction. That it is utilized is shown by the fact that the heat of combination of the resultant chemical compound must be the same whatever the condition of the metal. Hence less chemical energy is required for the solution of a strained metal, and the reaction is promoted by the state of the strain.

The validity of this reasoning is dependent upon the principle of the conservation of energy. As a result of my studies in the phenomena of recrystallization,[a] I became convinced that strained minerals are more readily acted upon by underground solutions than unstrained minerals. (See pp. 690–692.) Barus's experiments already cited suggested the above explanation. I then predicted that experiments would show that strained metals are more readily acted upon chemically than unstrained ones, and asked that this prediction be tested experimentally. This Mr. Hambuechen has done in reference to iron, with the following results:

> The application of stress to metals causes an increase in chemical activity, this increase being especially marked after the elastic limit has been reached.
>
> It is possible to get a curve showing the relation of electro-motive force to strain which is similar to that of stress to strain.
>
> There is a definite relation between the electrical potential of iron toward an electrolyte and the amount of energy stored up in the metal through the application of stress.[b]

Thus complete experimental confirmation of this prediction is made so far as iron is concerned; and it can hardly be doubted that this illustrates the general principle above given.

Applying the above principles to strain and chemical action, it may be said that in so far as minerals are strained either within or beyond the elastic limit, this potentializes energy and puts such minerals into a condition more favorable for chemical reactions than unstrained minerals. All rocks, except at the very surface of the earth, are under stress, and therefore strained to some extent at all times. It is true that the amount of stress may not be great within a few meters of the surface; but with increase of depth the average amount of stress becomes more important. In most cases of ordinary horizontal rocks near the surface it is customary

[a] Compare Van Hise, C. R., Metamorphism of rocks and rock flowage: Bull. Geol. Soc. America, vol. 9, 1898, p. 300.

[b] Hambuechen, Carl, An experimental study of the corrosion of iron under different conditions: Bull. Univ. of Wisconsin No. 42 (Engr. ser., vol. 2, No. 8), 1900, p. 255.

to regard them as practically free from stress and strain. However, not infrequently rapid deformation by uplift of an arch or by fracture when a few meters of load is removed, as at the Chicago drainage canal and at the combined lock of Appleton,[a] shows that such rocks are under very considerable stress, and therefore must be strained.

Not only are rocks generally under stress, but because of the complexity and variability of rock compositions, structures, and textures, wherever rocks are under stress the amount of stress and therefore of strain continually varies with changing direction and changing position. Variable amount of strain is therefore a universal law. In so far as any mineral particle is strained to a greater degree than an adjacent mineral particle of the same kind similarly strained, the particle under greater strain is more rapidly altered by chemical action. In so far as any portion of a mineral particle is strained to a greater degree than another portion of the same particle similarly strained, the part under greater strain is more rapidly altered by chemical action. Finally, for the same mineral particle or some part of the same the strain varies continually during deformation.

From the foregoing it follows that the almost universal state of strain, and the not less universal variability in the amount of strain, are of the most profound significance in metamorphism. (See Chapters VI, VII, VIII.)

Strain with rupture.—Where deformation produces rupture, another feature enters, also favorable to chemical action. Rupture is favorable to chemical action since thereby the surface exposed to the underground waters is inversely as the average diameter of the mineral particles. Granulation very greatly increases the surface of action.

Readjustment of particles.—The readjustment of the rock particles with reference to one another can hardly fail to give better opportunities for the chemical action of the ground waters; for during the adjustment the water will necessarily be moving and will come in contact with a succession of mineral particles, and thus promote chemical interchange. Hence I conclude that mechanical action is favorable to metamorphism by chemical action, whether the deformation be strain without rupture, with rupture, or merely readjustment of the rock particles, or, finally, any combination of these.

[a] Cramer, Frank, On the rock fracture at the Combined Locks mill, Appleton, Wis.: Am. Jour. Sci., 3d ser., vol. 41, 1891, pp. 432–434.

INDIRECT HEAT EFFECT.

It is a well-known law that mechanical action develops an equivalent amount of heat, except for the part of the energy which is potentialized. It has already been seen that heat is ordinarily favorable to chemical action. Therefore mechanical action promotes chemical action, because it develops heat and raises the temperature. Indeed, the heat developed by mechanical action is frequently one of the most important favorable conditions for metamorphism. It will be shown (Chapter VIII, p. 740) that where mechanical action is strong the complete recrystallization of rocks may occur much nearer the surface than under quiescent conditions. This result is largely attributed to the rise in temperature due to deformation, which results in vastly greater efficiency of the water as an agent of chemical action.

It therefore becomes of the utmost importance to consider to what extent the temperature is raised in the rocks by mechanical action.

The heat, as already intimated, is produced by the transformation of work into heat as a result of straining the rock particles within the elastic limit, by rupturing them, and by their frictional movements over one another. Mallet[a] has held that the heat thus developed may be sufficient to liquefy rocks by aqueo-igneous fusion. He thus accounts for the crystallized cores of many mountain ranges. He even holds that the material fused by mechanical action may intrude the adjacent solid rocks. LeConte follows Mallet in this belief. It may be theoretically possible that rock material can be ground so fine as to develop sufficient heat to fuse it. However, as explained (Chapter VIII, pp. 728–732), we have no evidence in the field that this has occurred. It is shown (Chapter VIII, pp. 690–696), that when the temperature of water-saturated rocks rises a certain amount, readjustment occurs, not by mechanical subdivision and grinding of the particles over one another, but by recrystallization. The process is thus chemical, not mechanical, and the expenditure of energy and the consequent development of heat are far less than by the former process. However, it is probable that, as a result of the interior kneading of rocks, the temperature may be materially increased, perhaps several hundred degrees beyond the normal temperature which obtains as a result of the depth of

[a] Mallet, Robert, Volcanic energy; an attempt to develop its true and cosmical relations: Philos. Trans. Royal Soc. London, vol. 163, 1873, pp. 147–227.

burial. And it is certain that the temperature can be very materially increased, and therefore that the chemical activity is enormously increased.

NATURE OF THE CHEMICAL REACTIONS.

Pressure influences chemical reactions under the following law: If a chemical system be compressed at a constant temperature, there follows a displacement of the equilibrium in that direction, which is associated with a diminution of volume. This law in relation to pressure and chemical activity may be stated in a more general form, as follows: "Those chemical forces are strengthened by compression which condition a diminution of volume; and those chemical forces are weakened by compression which condition an increase in volume."[a] In other words, so far as pressure influences chemical reactions, changes go on in directions which produce smaller volumes. Therefore pressure at all times and places is influencing chemical reactions in the direction of the production of more condensed systems. It has been seen (Chapter II, pp. 48–49) that pressure alone, without the presence of solutions, may produce reactions under this law. However, in nature, the vast majority of reactions under the law are accomplished through the agency of water. The importance of water in this connection is well illustrated by Spring's experiments upon the consolidation of clay when dry and wet. By pressure upon moist clay confined in a cylinder he was able to consolidate the clay into a body as compact as a piece of shale—indeed, so compact that it was difficult to scratch it with the finger nail. But using the same pressure upon dry clay he produced a substance so little consolidated that it was easily scratched with the finger nail. In the case of the moist clay, he attributed the consolidation to the escape of the plastic material about the piston, and to the precipitation of material from solution at the moment of escape.[b] Spring's explanation therefore does not introduce chemical readjustment of the compounds. However, it will be seen that pressure does promote chemical interchange, producing compounds which are, on the average, denser than the original ones. This, as will be shown on the following pages, is believed to be a dominant process for a great many chemical reactions

[a] Nernst, W., Theoretical chemistry, translated by C. S. Palmer, Macmillan Co., New York, 1895, p. 567.

[b] Tolman, C. F., jr., Professor Spring on the physics and chemistry of solids: Jour. Geol., vol. 6, 1898, p. 323.

resulting from pressure as the chief motive force; and it may be that chemical interchange is one of the processes which explain the consolidation of the clay in Spring's experiment.

In the rocks a smaller volume may result in either of two ways: Material may be taken into solution and deposited in a more compact form without change in chemical composition, or with change in chemical composition.

SMALLER ROCK VOLUME AS THE RESULT OF SOLUTION AND DEPOSITION WITHOUT CHANGE IN CHEMICAL COMPOSITION.

It has already been explained (pp. 77–78) that pressure promotes solution in case the volume of the solution is less than that of the solvent and solid, and that pressure promotes precipitation in case the volume of the solution is greater than that of the solvent and solid. Thus the solubility of a salt increases with pressure, provided the dissolving is associated with a contraction of the volume of the solution plus the salt; and, conversely, the solubility decreases if the separation of the salt (from the solution) is associated with a diminution of the volume of the system.[a] In ground solutions the general law is that the volume of the solution is less than that of the substances dissolved and the water. It follows from this law that pressure in rocks, the interstices of which are filled with water, promotes recrystallization and condensation.

The production of a smaller rock volume without change in chemical composition may occur where the recrystallization and condensation take place without change of minerals, and where the recrystallization and consolidation take place with change of minerals.

Recrystallization and condensation without change of minerals.—As an illustration of the principle, we may consider a stratum of unconsolidated crystallized calcium carbonate over which is a layer of water saturated with calcium carbonate. Inasmuch as the calcium carbonate is porous, the water in the rock is free to move and is under the pressure of the hydrostatic column above it. The particles of $CaCO_3$ are under this pressure, and also that of the solid above All the water in the crevices and pores small enough to hold water by capillarity is under both the pressure of the water and in part that of the rock. This water is saturated under this pressure, and it can hold more substances in solution than the water under less pressure. An interchange

[a] Nernst, W., Theoretical chemistry, translated by C. S. Palmer, Macmillan Co., New York, 1895, p. 567.

is constantly carried on between the free and the capillary water, and as the capillary water becomes free it is supersaturated and deposits some of its load in the interstices of the rock. But gravity ever pulls the material downward, and although this process is not rapid, it is continuous, and in course of time the particles are cemented. A solidified and recrystallized limestone is produced. Evidently the greater the pressure the more rapid and complete is this change.

Another example of solidification without change in mineral composition is the change of snow or separate ice crystals where mingled with water to solid ice, as at the head of glaciers. Ice has its melting point lowered by pressure. Where the granules are under more than the average pressure some of them melt. The water flows out into the free spaces and is again frozen. Or, as expressed above, under more pressure more of the ice is dissolved in the water than under less pressure. When the pressure is relieved in the more open spaces the ice is reprecipitated.[a] As the process goes on the particles are finally cemented. This process, like that of the recrystallization of limestone, is continuous, and finally the separated snow granules are transformed to continuous ice.

Recrystallization and condensation with change of minerals.—Recrystallization and condensation with change of minerals but without change in chemical composition may take place by precisely the same processes as already given. The resultant minerals, where the inducing cause is pressure, are more compact than the original minerals. Illustrating this principle, pressure induces the transformation of amorphous calcium carbonate to calcite. Similarly, pressure may induce the transformation of many other amorphous substances to crystalline forms. Pressure also induces minerals to change to forms having higher specific gravities. Thus pressure tends to transform tridymite, sp. gr. 2.28–2.33, to quartz, sp. gr. 2.653–2.660; and marcasite, sp. gr. 4.85–4.90, to pyrite, sp. gr. 4.95–5.10. (See pp. 220–221, 215.)

We may also safely argue that, where the pressure is great, minerals are not likely to crystallize in forms having low specific gravities. Thus under great pressure it is to be expected that silica will crystallize as quartz and not as tridymite. Doubtless this principle explains why quartz is always found in the plutonic rocks, and why tridymite often is

[a] Le Chatelier, in Theoretical chemistry, by W. Nernst, p. 654. Zeitschr. phys. Chemie, vol. 9, 1892, p. 335.

found in the volcanic rocks. The plutonic rocks crystallize under conditions of great pressure, while the volcanic rocks crystallize under conditions of moderate or slight pressure. It would be interesting to know the relations of quartz and tridymite in the matter of depth in the lavas, and therefore in reference to pressure at the time of crystallization.

SMALLER VOLUME AS THE RESULT OF SOLUTION AND REDEPOSITION WITH CHANGE IN CHEMICAL COMPOSITION.

Pressure inducing chemical reactions involving changes in chemical composition may produce crystallization and condensation of amorphous compounds and recrystallization and condensation of crystallized compounds.

Crystallization and condensation of amorphous compounds.—In general the amorphous compounds occupy more volume than their complex crystalline equivalents. "Therefore, since the crystallized state is generally that which takes the smallest volume, pressure aids crystallization."[a] According to Delesse, in passing from the crystalline to the glassy state, granite decreases in density 9 to 11 per cent, syenite 8 to 9 per cent, diorite 6 to 8 per cent, dolerite 5 to 7 per cent, and trachyte 3 to 5 per cent.[b] Thus glass occupies from 3 to 11 per cent more volume than the equivalent crystallized rocks. It therefore follows that pressure is one of the potent forces which result in the devitrification of glass. In general it may be said that rocks near the surface, whether original magmas, sediments, or schists and gneisses partly altered in the belt of weathering, very frequently contain amorphous products; whereas rocks which have been altered while deeply buried rarely contain any considerable quantity of amorphous material. It is believed that the explanation of the difference is largely due to difference in pressure. At depth where pressure is forceful the amorphous products which occupy more space than their crystallized equivalents either have not formed or if formed at the surface and deeply buried have become crystallized, the pressure being one of the important forces in the process.

Recrystallization and condensation of crystallized compounds.—Pressure may induce chemical action upon crystallized compounds, producing recrystallized products of a different kind and with more compact molecules, and therefore of greater specific gravity. In some cases the recrystallization has occurred

[a] Tolman, C. F., jr., Professor Spring on the physics and chemistry of solids: Jour. Geol., vol. 6, 1898, p. 320.

[b] See Dana, J. D., Manual of geology, American Book Co., 4th ed., 1895, p. 265.

at least twice. After one set of compounds was produced recrystallization again occurred, producing heavier compounds. The first change may be illustrated by the rearrangement of minerals which constitute mud so as to produce mica, quartz, and feldspar, and the second stage may be illustrated by the development from the latter rock of the still heavier minerals, garnet, staurolite, etc. (See p. 685.) However, the process of recrystallization in nature works in connection with more rapid solution of minerals where strained (see pp. 95–98) and with other forces. Its full consideration is therefore deferred to Chapter VIII (pp. 686–698).

GENERAL STATEMENTS.

Where pressure is unimportant, as near the surface of the earth, the chemical reactions are ordinarily controlled by other factors than pressure; but as the pressure increases, due to depth below the surface or other causes, it becomes a more and more important factor in the reactions which occur. But it is shown in Chapter VI, on "Weathering," that pressure may be an important factor in chemical reactions comparatively near the surface. This is illustrated by granitic rocks in the District of Columbia, described by Merrill,[a] which when brought to the surface underwent rapid disintegration, hydration, and expansion. The pressure of a few feet of rock was apparently sufficient to prevent the completion of these reactions, and thus it is clear that the adjustment between chemical reaction and pressure may be very delicate.

However, as explained in Chapter VI, chemical reactions near the surface do extensively take place with expansion of volume, and therefore in spite of some pressure. But it is also shown (Chapter VIII) that the pressure becomes a more and more potent factor in controlling the reactions; and, finally, that there exists a lower zone of anamorphism in which this is the dominant force. In this zone the chemical changes so take place as to lessen the volume of the compounds, and therefore to produce heavy minerals. Moreover, the reactions which occur in this lower zone are frequently just the reverse of those which take place in the upper zone, where pressure is unable to control, or the reactions in the two zones reverse each other.

[a] Merrill, G. P., Disintegration of the granitic rocks of the District of Columbia: Bull. Geol. Soc. America, vol. 6, 1895, pp. 322–332.

HEAT.

Heat is a very important factor in chemical action. In the heat factor two points are involved: first, the general effect of heat; and, second, the effect of change in temperature in consequence of the reactions.

As to the first of these, *in the lithosphere* the higher the temperature in general the more rapid the alteration. To this law there may be exceptions, but none are positively known to me.

As to the second point, the chemical effect due to the change in temperature in consequence of a reaction is much more complicated.

In considering whether heat be liberated or absorbed as a result of a chemical reaction it is necessary to take into account the heat changes in solution, the heat changes in precipitation, the heat changes in mixing solutions, and the heat effects of chemical reactions.

"By the heat of solution is meant the quantity of heat produced by the solution of 1 gram molecule of a substance in a large quantity of the solvent."[a] It has already been seen that in general the volume of the solvent and salt is greater than that of the solution, and that in this case there is usually liberation of heat and consequently rise in temperature; but in exceptional cases the volume of the salt and solvent is less than that of the solution, and in this case there is generally absorption of heat, and consequent fall in temperature. The total effect as to the liberation or absorption of heat depends upon whether the total of the factors, change in volume, change of the solid to its dispersed form in the solution, and the heat factor of dissociation, provided this occurs, is plus or minus. Decrease of volume tends to liberate heat; increase of volume tends to absorb heat. The change from the solid to the dispersed state of solution absorbs heat. The supposed dissociation of a substance into its ions is regarded as attended with either a liberation or an absorption of heat, though liberation is held to occur more frequently.[b]

In precipitation the heat effect is just the opposite from that of solution and is equivalent to the heat effect of the solution of an equal amount of the like salt. "In general, in comparing substances which are chemically analogous and soluble with difficulty, the heat of precipitation (=the negative value of the heat of solution) is the greater the more insoluble

[a] Nernst, W., Theoretical chemistry, translated by C. S. Palmer, Macmillan & Co., London, 1895, p. 503.

[b] Nernst, cit., p. 562.

the substance is."[a] If this law be applicable to quartz and to silicates it is of great importance in metamorphism, because these are the substances most largely dissolved and deposited by the ground water, with the possible exception of the carbonates.

As to the heat relations when two solutions are mixed, Ostwald states that in mixing solutions heat is produced by the work between the heterogeneous molecules, and heat is used in separating and spreading out the homogeneous molecules. The sum of these may be positive or negative, but in most cases the former is the case, and hence the two liquids usually become warmer when they are mixed.[b] Upon the same point Nernst says: "No heat phenomena result from the mixture of salt solutions [provided that no precipitate (and no volatile compound) is produced]."[c]

When chemical reactions occur there is a certain amount of heat of formation of the compounds. "By the 'heat of formation' of a chemical compound is meant the quantity of heat which is given off in the formation of the compound from its respective ingredients."[d] "The 'heat-toning' of a reaction is equal to the sum of the resulting heats of formation minus the sum of the heats of formation of the vanished molecules."[d] In whatever way a chemical result is accomplished, and however many the stages of process of the change, "the energy differences (and therefore the heat differences) between two identical conditions of the system must be the same, independently of the way by which the system is transferred from one condition to the other."[e]

This last is an important law so far as the work of ground waters is concerned, for in most cases we know only the opening and closing stages of the processes of alteration, and can ascertain whether the heat effect of a reaction is plus or minus only by comparing the heat required for the production of the original minerals with that required for the production of the secondary minerals, and their gaseous and fluid by-products.

While the above gives the conclusions as to the heat effect of individual reactions, the reaction which is likely but not certain to obtain at moderate pressure and temperature is covered by the rule of Berthelot. He says, "Every chemical change gives rise to the production of those

[a] Nernst, W., Theoretical chemistry, translated by C. S. Palmer, Macmillan & Co., London, 1895, p. 504.

[b] Ostwald, W., Solutions, translated by M. M. Pattison Muir; Longmans, Green & Co., New York, 1891, p. 308.

[c] Nernst, cit., p. 508. [d] Nernst, cit., p. 505. [e] Nernst, cit., p. 496.

substances which occasion the greatest development of heat."[a] And therefore, "other things being equal, there is the more chance that a substance can be formed, the greater its heat of condensation."[b] While these are the usual rules, they are not broad enough to cover the reactions of metamorphism under all pressures and temperatures. A more general statement of the law as to the relations of heat and chemical reactions is that of van't Hoff: "On the whole, the preponderating chemical reactions at lower temperatures are the combinings (associations) which take place with a development of heat, while the reactions preponderating at higher temperatures are the cleavings (dissociations) which take place with the absorption of heat."[c] The meaning of this law may be illustrated by the following reactions: At ordinary temperatures CO combines with O, producing CO_2, with great liberation of heat; at very high temperatures CO_2 dissociates into CO and O, with very great absorption of heat. This illustration makes it clear, as stated by Nernst, that to cover all cases van't Hoff's law must replace that of Berthelot, above given. Still more general laws as to the relations of heat and chemical reactions are the following: "If we heat a chemical system, at constant volume, then there occurs a displacement of the state of equilibrium, and in that direction towards which the reaction advances with absorption of heat."[d] "Those chemical forces which condition a development of heat will always be weakened by an increase of temperature; and, conversely, those which condition an absorption of heat will be strengthened by such an increase in temperature; and it is this fact which, primarily, gives the preceding proposition its universal validity."[d] "If we heat the system, therefore, the reaction which takes place will be accompanied by absorption of heat; if we cool the system, the corresponding reaction will develop heat."[e]

Now that the general laws covering the mutual influences of heat and chemical action have been given, we may consider in more detail their meaning. The speed of the reaction is commonly increased much more rapidly than the increase in absolute temperature. Thus, the speed of reaction of two similar solutions, one of which is at higher temperature

[a] Nernst, cit., p. 581, quoting Berthelot.
[b] Nernst, cit., pp. 585–586.
[c] Nernst, cit., p. 583.
[d] Nernst, cit., p. 566.
[e] Ostwald, W., Outlines of general chemistry, translated by James Walker, 2d ed., Macmillan & Co., London, 1895, p. 312.

than the other, may be far greater in the solution at high temperature than would be calculated from the relative absolute temperatures of the solutions.

Indeed, the velocity of a chemical reaction commonly increases enormously with moderate increase of temperature. The partial explanation of the phenomena lies in the fact that in most cases the reactions themselves, as already seen, develop heat, which immediately reacts to increase the kinetic energy of the remaining molecules, and this again increases the kinetic energy of the molecules, and so on, there being continual action and reaction between the chemical activity and the rising temperature.

Another illustration of the very important way in which increase of temperature increases chemical action is the increased activity of substances which at low temperatures are relatively inert. While at ordinary temperatures carbon dioxide replaces silica in silicates, at temperatures of 100° C. silica, if present in abundance, may replace carbon dioxide in carbonates.[a] While this is explained in part by the increase of activity of silicic acid with increase of temperature, it doubtless in part is explained by the law of mass action and the increased volatility of carbon dioxide at higher temperatures.

If the dissociation theory be true, a third factor which may have some effect in producing speed of reaction with increase of temperature is the increase in the amount of hydrolysis with increase of temperature. This is illustrated by ferric chloride, which at low temperatures is regarded as but little hydrolized, but at high temperatures is believed to be hydrolized to a perceptible extent according to the equation:

$$Fe_2Cl_6+6H_2O=Fe_2(OH)_6+6HCl.$$

The presence of the ferric hydroxide is shown by the color of the solution.[b] In a similar manner, the carbonates and silicates are believed to be hydrolized to a much greater extent at high temperatures than at low temperatures. This is illustrated by calcium carbonate, which in solution at high temperatures gives a strong alkaline reaction of calcium hydroxide, and this is regarded as evidence of strong hydrolysis. It is possible that hydrolysis is an important factor in the reactions which take place in the different zones of metamorphism.

[a] Bischof, Gustav, Elements of chemical and physical geology, translated by Paul and Drummond, Harrison & Sons, London, vol. 1, 1854, p. 6.

[b] Ostwald, W., Grundlinien der anorganischen Chemie, Engelmann, Leipzig, 1900, p. 583.

While in general, speed of chemical change is promoted by rise of temperature, as indicated by the second part of van't Hoff's law, there is a limit to the increase of speed due to action and reaction between chemical change and heat, for when the temperature becomes too high a reverse tendency is set up, since the compounds formed by the chemical reactions frequently can not exist at very high temperatures. In such cases the rate of reaction may cease to increase with increase of temperature, and, indeed, the reactions which obtain at lower temperatures may be reversed.

Just as a slight increase of temperature may enormously increase the speed of chemical reactions, so a slight decrease of temperature may very greatly lessen the speed of reactions. Therefore, if the reaction be one which itself absorbs heat, and thus lowers the temperature, the slight decrease in the kinetic energy of the molecules may greatly retard the speed of the reaction.

At the very moderate temperatures which generally prevail within the outer part of the crust of the earth the heat resulting from the chemical changes does not become so great as to stay the reactions. Therefore, it may be said that the chemical reactions which take place with liberation of heat promote metamorphism, and those which take place with absorption of heat retard metamorphism. The great importance of these two tendencies, as applied to rocks, will be shown on subsequent pages in connection with the discussion of the zones of katamorphism and anamorphism.

On subsequent pages it will be seen that in the zone of katamorphism the first part of van't Hoff's law or the rule of Berthelot generally prevails in the alterations of rocks for a considerable distance from the surface. That is to say, on the whole the preponderating chemical reactions are those which take place with the liberation of heat. Moreover, as a consequence of increase of heat with depth, at a very moderate depth the temperature is rather high. Also, igneous rocks give high temperatures to the surrounding rocks and solutions. As a result of any of these causes, water may reach the moderate temperature of 100° to 200° C., and such temperatures increase the activity of water in an amazing degree. (See pp. 79–81.) Thus we see that in the zone of katamorphism the heat of chemical action, and that derived from the interior of the earth through conduction and convection by means of magma and water, all work together to increase the speed of chemical action, and therefore to hasten metamorphism.

However, it will also be seen that in the zone of anamorphism, with pressure as a dominant factor, reactions very generally occur with the absorption of heat under the second part of van't Hoff's law. Thus, in this zone the heat effect of the chemical reactions is to stay metamorphism. But while the reactions which occur at depth are very generally those which absorb heat, it must be remembered that in the zone of anamorphism the amount of heat available, due to increase of heat with depth and to the difficulty with which the heat escapes from intrusive rocks, is very great. Therefore, notwithstanding the fact that the chemical reactions themselves absorb heat, the temperature is much higher than in the upper zone. Consequently one would expect that the chemical activity would be greater in the zone of anamorphism than in the upper zone of katamorphism; and with these expectations the facts correspond. (See pp. 660–661, 690–692, 749–751.)

RELATIONS OF CHEMICAL ACTION, MECHANICAL ACTION, AND HEAT.

All transformations of material upon the earth, provided all the energy factors be taken into account, involve the expenditure of energy and the dissipation of part of it as heat. If this were not true it would be possible to manufacture an engine by means of which an equal or greater amount of energy is available for work than is expended in driving the engine, and perpetual motion would be possible. In metamorphism of rocks, in order that the above general statement as to the expenditure of energy shall be true, it is necessary to take into account the chemical force, mechanical force, and heat which promote the transformations. In those cases where a transformation of material does not at first sight appear to demand the expenditure and dissipation of energy, this is due to the fact that some of the energy factors are overlooked.

It has been noted that chemical actions are reversible, and it will be seen subsequently that chemical reactions which take place on a large scale in the zone of katamorphism are reversed in the zone of anamorphism. When a chemical reaction takes place, and later that reaction is reversed and the cycle is repeated, exterior energy must have been expended and dissipated. To illustrate, let us consider the reversible reaction

$$Fe_2O_3+3H_2O \rightleftarrows Fe_2O_3.3H_2O.$$

The reaction may advance from left to right by the expenditure of chemical energy alone, and as a result of the process heat is liberated.

However, to reverse the reaction or to advance it from right to left requires the expenditure of a greater amount of external energy than the chemical energy expended in the first reaction. In the reaction given the available external energy may be from one of two sources—heat or mechanical action. The ferric hydrate may be broken into ferric oxide and water by heating. Also, if the pressure be very great and water have a chance to escape the same transformation may take place by the expenditure of mechanical energy. Doubtless in nature in many cases both of these forces unite in the process, but whether the dehydration takes place as a result of the expenditure of heat energy alone or mechanical energy alone, or the two combined, a greater amount of energy must be expended than the chemical energy expended in the hydration of the iron. Hence, when hydration takes place in the zone of katamorphism energy is expended. This is potential chemical energy. When dehydration takes place in the zone of anamorphism, reversing the first process, energy is also expended. This is either potential mechanical energy or the energy of heat, or the two together. I say potential mechanical energy, for I have held in another place that all earth movements, provided all the factors are taken into account, result in bringing the material moved nearer the center of the earth, and therefore the energy expended is the potential gravitative energy of position.[a]

The reasoning applied to the case of hydration and dehydration of ferric oxide is applicable to every other reversible reaction in metamorphism; hence, when we take all the energy factors into account, at the end of the process energy has been expended. Furthermore, a part of this energy during the process has been transformed to heat and dissipated; for in all transformations of energy there is an inevitable tendency for some of the energy to run down into the lowest form, heat, a portion of which is lost.[b]

In conclusion, therefore, in the zone of katamorphism, while chemical reactions frequently take place which liberate heat and expand the volume, and in the zone of anamorphism chemical reactions take place which absorb heat and condense the volume, in both zones alike when all of the energy

[a] Van Hise, C. R., Earth movements: Trans. Wisconsin Acad. Sci., Arts, and Letters, vol. 11, 1898, pp. 487, 488, 512–514.

[b] Daniell, Alfred, A text-book of the principles of physics, 3d ed., Macmillan Co., New York, 1895, p. 51.

factors are taken into account the reactions take place in such a way as to demand the expenditure of energy and the loss of a part of it.

Where chemical force, mechanical force, and high temperature work together, with an abundance of water, as an agent of metamorphism, the speed of rock metamorphism is very great as compared with the slow alterations which occur at the surface of the earth. For instance, Barus finds that water at temperatures above 185° C. and under high pressure is capable of very rapidly uniting with glass, forming a new compound, which at these temperatures is liquid, and which he calls water glass. In a retort he combined 210 grams of glass and 50 grams of water in twelve hours at a temperature of 210° C. into water glass, which was liquid at that temperature, but became a clear solid at ordinary temperatures.[a]

Not only amorphous compounds but crystalline minerals also are acted upon rapidly at such temperatures and pressures. At 180° C., with pressure sufficient to keep the water in the liquid form, Lemberg[b] has completely dissolved zeolites in pure water. Under similar conditions it has also been shown that pure water acts rapidly upon powdered anhydrous silicates. For instance, Forchhammer showed that water under these conditions dissolves potassium silicate from powdered orthoclase.[c]

Within the zone of rock flowage temperatures and pressures higher than those with which these experiments have been made are available, and it is therefore to be supposed that in the zone of anamorphism there is rapid transformation of the minerals to forms which are relatively stable under the conditions obtaining at any given time and place. So far as substances have not a compact state of aggregation energy is potentialized. Pressure being a very potent factor, the transformations would of course be into condensed systems, or into minerals having high specific gravity and probably complex molecular structure. It is evident that in the forces of chemical action, mechanical action, and heat, and the agent, water, we have adequate causes for the crystallization of amorphous compounds, for the recrystallization of strained minerals, and for the recrystallization of highly

[a] Barus, C., The compressibility of liquids: Bull. U. S. Geol. Survey No. 92, 1892, pp. 78–84. Hot water and soft glass in their thermo-dynamic relations: Am. Jour. Sci., 4th ser., vol. 9, 1900, pp. 164–65.

[b] Doelter, C., Allgemeine chemische Mineralogie, Wilhelm Engelmann, Leipzig, 1890, p. 189.

[c] Forchhammer, G., Ueber die Zusammensetzung der Porcellanerde und ihre Entstehung aus dem Feldspath: Poggendorff, Annalen, vol. 35, 1835, p. 354.

potentialized minerals to lower potentialized forms. These changes are illustrated by the passage of glass to a crystalline form, by the passage of minerals from a strained to an unstrained condition, and by the passage of minerals of low specific gravity to minerals of higher specific gravity.

PRECIPITATION.

From solutions, by changing conditions, solids may separate. This process is called precipitation. Since precipitation from ground water solutions is of the utmost importance in metamorphism, it is necessary to consider fully the conditions under which precipitation takes place. It has already been seen that in solutions the ingredient which is present in excess is called the solvent and the ingredients which are subordinate are the substances dissolved. When from solutions the substance in excess, or the solvent, separates, this is called a freezing of the solution. When in the solution the substances dissolved first separate, this is called crystallizing out of the materials dissolved. "The processes of freezing and of crystallizing out are both to be considered from the same point of view; and when we are not dealing with dilute solutions where one ingredient is present in large excess, but with a mixture, where both ingredients are present in about the same proportions, then we would be in actual doubt whether the separation should be regarded as a freezing (of the solvent) or a crystallizing out (of the substance dissolved), or perchance of both processes."[a]

The necessary condition for precipitation is supersaturation; for if a solution be not saturated it will take more material into solution; but if a solution be sufficiently supersaturated some of the material must be thrown down or be precipitated. If solids are present similar to the compounds in solution, considerable supersaturation does not occur. This is very frequently the case with ground solutions. Under such circumstances the salts in solution separate out upon the minerals already present, or the minerals grow. At any given pressure and temperature, provided the changes occur slowly, equilibrium is nearly retained by this continuous adjustment. This relation between minerals already present and solutions is one of the most important factors which control the growth of minerals which are present. If, for instance, in a complex solution containing

[a] Nernst, W., Theoretical chemistry, translated by C. S. Palmer, Macmillan Co., New York, 1895, p. 414.

various ions there are also various crystalline minerals, the moment that the solution becomes supersaturated with reference to several ions which may unite to produce one of the solids present, this union will take place, the material will be precipitated upon the minerals of that kind, and thus they will grow.

This process of mineral growth applies alike to minerals in magmas and to minerals in sedimentary rocks. If, for instance, in a magma plagioclase and pyroxene individuals once begin to form, they may grow to large size and produce a gabbro. In a sedimentary rock in which quartz and feldspar particles are present and the solutions are of a kind which furnish constituents for their growth, these particles are likely to be enlarged.

Supersaturation, and consequently precipitation, may result in various ways, of which the following are the more important: (1) Precipitation by change of pressure, (2) precipitation by change of temperature, (3) precipitation by reactions between aqueous solutions, (4) precipitation by reactions between aqueous solutions and gases, and (5) precipitation by reactions between solutions and solids.

PRECIPITATION BY CHANGE OF PRESSURE.

Change of pressure may result in supersaturation, and therefore in precipitation. Where the volume of the solution is less than that of the solvent and substance dissolved, decrease of pressure is favorable to precipitation. Where the volume of the solution is greater than that of the solvent and substance dissolved, increase of pressure is favorable to precipitation. The volume relations are opposite in the cases of the crystallization of minerals from solutions of ground water and the crystallization of minerals from magmas. In the case of substances dissolved in ground solutions the volumes of the solutions are commonly less than those of the solvent and the substances dissolved; therefore decrease of pressure is favorable to precipitation. But in the case of crystallization from magmas the volume of the solution is greater than that of the crystallized minerals; therefore pressure is favorable to crystallization.

In another connection it is suggested that under certain conditions water and magma are miscible in all proportions. (See Chapter VIII, p. 723.) In other words, there is every gradation from water containing compounds in solution to magmas containing subordinate amounts of water. If this

be so, ideally there must be a neutral point in which the volume of the material is the same whether as a solution or as a solid. In this case pressure would have no effect upon precipitation. However, the precipitation of any part of the material from a solution modifies the character of the remainder of the solution, and it is not to be supposed that a case is likely to occur in which crystallization of material takes place without there being any pressure effect.

Where circulating waters are descending the pressure is increasing, and where ascending the pressure is decreasing. Therefore, in the case of ordinary ground-water solutions the direction of water circulation which is favorable to precipitation is ascension.

PRECIPITATION BY CHANGE OF TEMPERATURE.

Change of temperature may result in supersaturation, and therefore in precipitation. In general, in ground solutions increase in temperature increases solubility. (See pp. 79–81.) Therefore decrease in temperature is favorable to supersaturation and precipitation. While this statement is true for most substances at temperatures below 100° C., and is correct for many substances at temperatures considerably higher than this, at very high temperatures the conditions are reversed for some substances. (See p. 79.) In the common case, that of precipitation with decrease of temperature, the freezing point of the solution is lower than that of the solvent.[a] Apparently the amount of lowering is proportional to the molecular weights, and is stated by Raoult as follows: "One molecule of any compound when dissolved in 100 molecules of a liquid lowers the solidification point of the liquid by an amount which is nearly constant, viz, 0.62°;" or, the molecular depression, when the solvent is to the solute as 1:100, is 0.62°.[b] In dilute solutions of salts in water, the molecular depression may be larger than this, in which case the substance is regarded by many as dissociated.[c] It was by the application of the principle of molecular depression that Kahlenberg and Lincoln were able to reach the conclusion already given (p. 87), that silica goes into solution as colloidal silicic acid. When the silicates are dissolved and

[a] Ostwald, W., Solutions, translated by M. M. Pattison Muir; Longmans, Green & Co., New York, 1891, p. 199 et seq.

[b] Ostwald, Solutions, cit., p. 208.

[c] Ostwald, Solutions, cit., p. 214.

decomposed by hydrolysis into colloidal silicic acid and metallic hydroxides, the latter (or, according to the dissociation theory, their ions) caused the molecular depression, which was unaffected by the colloidal silicic acid.

In precipitation from complex mixtures the substances do not solidify at the same time. The compounds crystallize in such order, and the separated solid is of such a character, that "the freezing point of the remaining liquid is lowered." [a] After one compound has separated another follows, which again lowers the freezing point, and finally a liquid is left with the lowest freezing point, and this liquid is the last compound to crystallize.

Change in temperature is the rule for underground circulating waters. The waters which are passing to lower levels are, on the average, becoming warmer. Waters which are rising to higher levels are, on the average, becoming colder. Also there are changes of temperature, both positive and negative, due to varying local conditions; for instance, the presence of intruded igneous rocks. Ascending waters are, on the whole, precipitating material, because they are losing heat. The increase in the capacity to hold material in solution with rising temperature, and the simply enormous increase in this capacity as the temperature becomes very high, have already been pointed out. (See pp. 79–81.) During the upward journey of the water the temperature continuously falls, and if the journey be long the total loss of heat is great, and the amount of precipitation is correspondingly large. Since the upward course of the water is likely to be in the larger openings (see p. 583), such as the spaces of porous sandstones, faults, joints, etc., we have the partial explanation of the filling of these openings in the belt of cementation. However, this general statement needs various modifications, dependent upon many variable factors. (See pp. 629–640.)

PRECIPITATION BY REACTIONS BETWEEN AQUEOUS SOLUTIONS.

It has already been seen that when solutions containing various salts are mixed the resultant solution will contain all the salts which can be made by the various combinations of their positive and negative ions. (See p. 68.) The first law of precipitation may be stated thus: When any combination of the various ions in a solution can form to a sufficient extent

[a] Nernst, W., Theoretical chemistry, translated by C. S. Palmer, Macmillan Co., New York, 1895, p. 111.

to be insoluble in the liquid present, such compound will be produced and precipitated. To illustrate, if a solution of $BaCl_2$ be added to a solution of Na_2SO_4, the ion Ba can unite with the ion SO_4 and produce the insoluble compound $BaSO_4$, which will be precipitated.

The above is a statement of the empirical facts. The explanation of these facts under the theory of dissociation is given by Ostwald as follows: In any given case there is a constant relation between the amount of a compound which can be held in solution and the number of free ions of that compound. Upon this statement are based the laws of precipitation from solutions. Says Ostwald:

> In solutions a state of equilibrium subsists between the ions of the electrolyte and the nondissociated portion. To take the simplest possible case, if we have a binary electrolyte C, which can break up into ions A' and B', and if a, b, and c represent the concentrations of these three constituents in a given solution, then the following simple formula holds good: ab=kc.
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> Now, the two kinds of ions are produced in equivalent quantities, in the above case, hence a=b. If, further, the total amount of the electrolyte =1, and α represents the ionized portion, then $a=b=\frac{\alpha}{v}$ and $c=\frac{1-\alpha}{v}$, v being the volume of the solution in which unit quantity (a molecular weight in grammes) of the electrolyte is contained. By carrying out the substitution we get the formula $\frac{\alpha^2}{(1-\alpha)}=kv$, which expresses the state of ionisation of an electrolyte at the dilution v.[a]
>
> In the saturated aqueous solution of an electrolyte we have a complex equilibrium. On the one hand the solid is in equilibrium with the nonionised portion of itself which is in solution, while on the other hand this nonionised portion is in equilibrium with the dissociated part—i. e., with the ions of the same substance. The first equilibrium comes under the law of proportional concentration, or, since we are dealing here with a substance of unalterable concentration on the one hand, the concentration of the nonionised portion in the solution must have a perfectly definite value. For the second equilibrium we have in the simplest case—i. e., when the ions of the compound are monovalent—ab=kc, a and b representing the concentrations of the ions and c the concentration of the nonionised portion.
>
> Now, since c is constant at a given temperature, as we have already seen, kc, and therefore ab, must be constant also. Equilibrium is thus established between a precipitate and the liquid above it when the product of the concentrations of the two ions, into which the precipitate falls, has a definite value. This product may be termed the solubility product for the sake of brevity.

[a] Ostwald, W., Foundations of analytical chemistry, translated by George McGowan, Macmillan & Co., London, 1895, p. 59.

If the electrolyte consists of polyvalent ions in the proportion mA:nB, the solubility product takes the form: $a^m b^n$= constant.[a]

From the foregoing follows Ostwald's statement of the first law of precipitation, already given: "Whenever in any liquid the solubility product of a solid is exceeded, the liquid is supersaturated with respect to that solid,"[b] and therefore precipitation of the salt follows. Of the various salts which may be precipitated from a solution, that one will be precipitated first whose solubility product exceeds its constant of solubility.

Ostwald illustrates this by the cases already cited: If a solution of $BaCl_2$ be added to Na_2SO_4, $BaSO_4$ will be precipitated. According to Ostwald's view, this happens because the solubility product of the ions in $BaSO_4$ is very small.

The second law of precipitation follows from the fact that "the solubility of one salt is depressed in the presence of another having a common ion."[c] This is equivalent to saying that "the solubility of each molecular species in a mixture is always smaller than for the particular species when alone."[d] Hence, when to a solution containing certain ions a solution is added which has an ion in common with one of those already in the solution, supersaturation and precipitation are promoted. An example of this is the addition of HCl to a solution of $BaCl_2$. The chlorine ion is common, and if the solution is near saturation before the HCl is added, $BaCl_2$ will be precipitated. Again, if one adds a saturated solution of $NaClO_3$ to a saturated solution of $KClO_3$, an abundant precipitate of the latter salt will form.

The above law is a general statement which includes the rule that "The addition to a solution of a liquid which is able to form a homogeneous whole with the solution causes precipitation of more or less of the substance in solution if that substance is insoluble in the liquid which is added."[e] This rule is illustrated by the same examples. It follows from this that "in order to precipitate a substance completely from its solution, an addition of an excess of the precipitant is an advantage."[f]

The converse of the second law of precipitation is: The solubility of a salt increases on the addition of a second salt containing no ion in common.

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[a] Ostwald, W., Foundations of analytical chemistry, translated by George McGowan, Macmillan & Co., London, 1895, p. 76.

[b] Ostwald, Foundations, cit., pp. 76–77.

[c] Nernst, W., Theoretical chemistry, translated by C. S. Palmer, Macmillan Co., New York, 1895, p. 446.

[d] Nernst, cit., p. 453.

[e] Ostwald, Solutions, p. 90.

[f] Nernst, cit., p. 449.

To illustrate: "If one adds some KNO_3 to $AgBrO_3$, a number of molecules of $AgNO_3$ and also of $KBrO_3$ will be formed. This will result in a diminution of the number of the molecules of $AgBrO_3$, which must be replaced from the solid salt," or the solubility will be increased.[a]

Cameron gives two illustrations of this converse which are of great importance in ground solutions:

Gypsum, which is essentially the salt calcium sulphate containing some water, is sparingly soluble in water. But the addition of an electrolyte with no common ion, such as sodium chloride, will considerably increase the solubility of the gypsum. Some experiments made in this laboratory have shown that in moderately strong brines containing only sodium chloride gypsum can be regarded as a soluble salt. The reason for this is readily seen when the substances which are formed are considered, both the calcium chloride and the sodium sulphate being very soluble salts. The transportation of large quantities of lime by the drainage and ground waters in arid regions where these salts are found is readily explicable from this point of view.

Calcium carbonate, so abundant and so important in nature, is dissolved in a precisely similar way; but the ionization of carbonates being relatively small, the effect is not so striking and relatively much less lime is transported in the solution. Treadwell and Reuter[b] have recently published investigations on this point and find the solubility of calcium carbonate in sodium chloride solutions does not become markedly large until considerable concentrations of the latter salt are reached. The effect of carbon dioxide in forming the more soluble bicarbonate of lime undoubtedly is an important element in this connection, but as the ionization is but little affected by its presence its influence must be small in the presence of such a salt as sodium chloride.[c]

PRECIPITATION BY REACTIONS BETWEEN AQUEOUS SOLUTIONS AND GASES.

Another case of precipitation occurring in nature follows as a result of mixing solutions, one of which is a gas which acts upon the compounds in the aqueous solution, producing ions of a different kind from those before present, and in some cases forming compounds, the solubility of which is so small that precipitation results. Perhaps the most important case of this kind is the mixing of oxygen with a solution containing salts of iron protoxide. As a result of this the iron is changed from ferrous to ferric form, and the latter is precipitated as a sesquioxide or hydrosesquioxide of iron. In the latter case hydration occurs simultaneously with oxidation.

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[a] Nernst, cit., p. 450.

[b] Treadwell, F. P., and Reuter, M., Ueber die Löslichkeit der Bikarbonate des Calciums und Magnesiums: Zeitschr. für anorgan. Chemie, vol. 17, 1898, p. 170.

[c] Cameron, F. K., Application of the theory of solutions to the study of soils: Rept. No. 64, Field Operations of Division of Soils, 1899, U. S. Dept. of Agric., 1900, pp. 150–151.

PRECIPITATION BY REACTIONS BETWEEN SOLUTIONS AND SOLIDS.

"If one pours a solution of KBr over solid AgCl, . . . the bromine existing in the solution will be largely replaced by chlorine, because as AgBr is much less soluble than AgCl an equivalent quantity of AgCl will be changed into AgBr. This is also established by experiment. If one knows the solubilities of AgCl and AgBr, then for a given concentration of KBr we may state the point of equilibrium which the system strives to reach."[a] Hence we conclude that if a salt, A, is treated with a saturated solution of another salt, B, a greater or less part of the salt B may separate out, the salt A being taken into solution at the same time. In this case "the active mass of the solid substance is a constant."[b] The meaning of this is that if any of a solid salt is present after the reaction has ceased there was sufficient to produce equilibrium between the salt and the solution.

An excellent case illustrating precipitation from solution in nature by the action of a solid, one of the most fundamental importance, is the partial dolomitization of the calcium carbonate of shells and corals by the sea waters, which contain both calcium and magnesium salts. In this case, under the law of chemical equilibrium, there is constant action and reaction between the magnesium salts in solution and the solid $CaCO_3$. The magnesium and calcium partially interchange, the calcium going into solution by uniting with the ions before combined with the magnesium, and the magnesium simultaneously uniting with the CO_3 ion before united with the calcium and thus being thrown down as $MgCO_3$. Thus the calcite is partially dolomitized.

This case of dolomitization well illustrates the principle that simultaneously with the precipitation of one element or mineral another element or mineral may be dissolved, one being conditioned upon the other. There are very numerous complicated cases of this kind which need investigation. (See pp. 203–206.)

The solids present exert an important influence in precipitation independently of the passage of elements of the solids into the solutions. That is to say, if there be solids present, even if none of the elements of any of such compounds pass into solution, these solids may influence the

[a] Nernst, W., Theoretical chemistry, translated by C. S. Palmer, Macmillan Co., New York, 1895, p. 452.

[b] Nernst, cit., p. 450.

nature of the precipitation. This statement is applicable both to compounds present in solutions before precipitation begins and to compounds formed by precipitation itself. Once any precipitate begins to form, particles of that precipitate are present and influence further precipitation, precisely as do other solids which were present before the precipitation began. The proof of the influence of the solids present is furnished by the very well-known tendency to the enlargement of mineral particles already existing in preference to the formation of new individuals.

The growth of mineral particles already present is probably connected with the phenomenon of adsorption, described on pages 64–65. It is there noted that the contact film of solutions with solids contains more than an average amount of material in solution. It may be suggested that this is due to the molecular attraction of the crystal for the molecules in solution, just as the adherent film of the liquid itself is due to the molecular attraction between the solids and liquids. As the particles in solution move about they continually impinge against the solids in the solutions. These particles thus come within the limits of the molecular attraction of the solids and are to a certain extent held, and hence the concentration. It would follow that the adherent films of liquid are likely to become supersaturated in advance of the remainder of the solutions. Under these circumstances the moment supersaturation is reached with reference to the compounds forming a given particle, these materials will be deposited upon the particle, and will grow. Precipitation immediately follows supersaturation of the concentrated film because of the orienting and selecting power of the mineral particle already existing. It is probable in the case of a given mineral that for compounds other than those which can unite to produce the mineral supersaturation can take place to some extent, and that from this slightly supersaturated adherent film this material may escape into the free solution. However, when such solutions become supersaturated in the presence of a mineral which could use them they would be thrown down. By this process is explained the selective power by which each mineral particle is able to take from solution material like itself and add it to itself; and also the fact that particles once formed abstract materials like themselves from solutions in preference to the formation of new particles.[a] The presence of any

[a] For explanation of adsorption see Ostwald, W., Grundlinien der anorganischen Chemie, Engelmann, Leipzig, 1900, pp. 387–389.

mineral species will prevent considerable supersaturation of the solution, so far as the compounds of that species are concerned. The result is that if there be materials in a solution which can unite to produce mineral species which are present they will do so. In this way the minerals control or guide to a considerable extent the character of the solids which are deposited, since when a certain mineral is absent, before that mineral can begin to be precipitated supersaturation must occur with reference to the chemical combination which composes it.

Therefore the mineral species which are present in a solution have an advantage over other kinds of minerals which are absent. To a less degree, minerals which are abundantly present have an advantage over those which are sparse. To illustrate, if quartz be present and the solutions contain ions of silica, it will be apt to abstract the silica from the solutions the moment supersaturation occurs. In the same way, if feldspar be present and there are ions of sodium, calcium, aluminum, and silica in proper proportions, these are likely to be grouped together to produce feldspar. Moreover, it appears to be the case that the feldspar may so nearly control that a closely analogous feldspar is produced, and twinning and other phenomena characteristic of the original grains be continued in the secondary growth. The same statements apply to hornblende, tourmaline, calcite, and, in fact, to all minerals in which a secondary growth has been noted. Of course, in a rock in which there are present a large number of mineral particles, the particular mineral which is formed will depend upon the various ions in the solution, their relative proportions, and the relative insolubility of the salts. For instance, tourmaline can not form unless the boric acid ions are present; hornblende can not be produced unless there are in the solution all the bases demanded by that mineral in sufficient abundance. Thus the particular mineral which forms depends upon a complicated adjustment of the mineral particles present, the ions present in the solution, their relative proportion, and the solubility of the mineral particles.

In the above chemical principle lies a partial explanation of the strange fact that minerals are so firmly cemented by material like the dominant original mineral. In quartzose sandstone the chief cement is silica; in feldspathic sandstone the chief cement is likely to be feldspar; in strongly hornblendic rocks one of the chief cements is hornblende, and so on. Another

important factor in the process is the extension of the rock masses from the places of solution to the places of deposition. For instance, in any rock which extends from the belt of weathering to the belt of cementation the water at the places of solution (especially the belt of weathering) would obtain material adapted to the enlargement of the minerals of the same rock at the place of deposition (especially the belt of cementation). Consequent upon the two factors above given, rocks in many instances are cemented by minerals like those present before cementation began.

SECTION 2. CIRCULATION AND WORK OF GROUND WATER.

UNIVERSAL PRESENCE OF WATER IN ROCKS.

It has already been explained at the opening of this chapter that water is the great dominating agent through which the greatest transformations are accomplished. Free water is present to some extent in all rocks within the zone of observation. That it is abundant in porous rocks is well known. Water has also the power to slowly penetrate the apparently solid rocks. Between the mineral particles there is space sufficient for water to make its way, and a small amount of water is found in the most massive and relatively impervious rocks.

Besides the free water in rocks, there is always present water in a combined form. The combined water varies from a small fraction of 1 per cent to several per cent. Commonly the combined water does not fall below 0.50 per cent, and seldom is higher than 8 per cent. It therefore appears that all rocks contain water, both in the free and in the combined form. The amounts of each of these are very variable. Bischof many years ago noted the penetration of basalt by water.[a] The permeation of apparently solid rocks by water is well illustrated by the readiness with which agate, chalcedony, and such materials are affected by a staining solution. When agates are boiled in colored solutions, the liquid makes its way through the minute subcapillary spaces so small that the microscope can not detect them, and the bands are differently tinted, the amount of deposited coloring material depending upon the relative sizes of the minute openings.

[a] Bischof, Gustav, Chemical and physical geology, translated by Paul and Drummond, Harrison & Sons, London, vol. 1, 1854, p. 10.

The water in rocks may completely or partly fill the openings. Where the openings of a rock are completely filled, the rock is saturated. Unless all the openings in a rock are subcapillary it will remain saturated only so long as it is surrounded or partly surrounded by the saturating liquid. If withdrawn from the saturating liquid, all the water may be drawn off by ordinary physical means except that adhering to the walls of the openings. This residual amount of water is called the water of imbibition. The difference between the water of saturation and that of imbibition, which, as will be seen, is the water which may flow somewhat readily, may be called the water of hygrometricity. In the rocks having subcapillary openings (see pp. 143–146) the attraction extends from wall to wall, and therefore the entire film of water in the spaces adheres to the rock particles, or is water of imbibition. In the rocks having subcapillary pores only, the water of imbibition and saturation is the same.

The next question which arises is as to the source of the ground water. On pages 661–668 reasons are given for the belief that the circulation in the zone of anamorphism, which corresponds to the zone of rock flowage, is very slow indeed. In this deep-seated zone decarbonation, dehydration, and to some extent deoxidation of the rocks take place. It is shown (see pp. 764–766) that with these exceptions, excluding igneous rocks, the composition of the rocks metamorphosed in the zone of anamorphism closely corresponds with their original composition, contrasting greatly in this respect with the rocks metamorphosed in the zone of fracture. From these and other facts it is certain that the circulation of water in the zone of anamorphism is very slow. However, it is probable that a large portion of the carbon dioxide and water liberated slowly makes its way into the zone of fracture. It is also explained that some water may join the zone of fracture through the agency of igneous rocks which enter this zone. But the amount of these supplies of water at any one time is small—indeed, insignificant compared with the amount required to keep up the active circulation which we know exists in the zone of fracture. Since, then, it can not be shown that any considerable fraction of the water of circulation of the zone of fracture is derived from the zone of rock flowage, we can only suppose that this water is derived from precipitation. The subterranean water is therefore predominantly of meteoric origin.

PORE SPACE OF ROCKS.

The pore space of rocks varies from a small fraction of 1 per cent to 50 per cent or more. The pore space in compact, strong, igneous rocks is exceedingly small. For instance, in fresh, strong granites the percentage of water absorbed by the dry rock varies from 0.08 to 0.20 per cent, which corresponds to a pore space of 0.20 to 0.50 per cent. The more compact limestones also contain very little pore space. Some of them absorb as small an amount as 0.20 per cent by weight of water, which corresponds to a pore space of about 0.55 per cent.

Ordinary compact limestones used for building material, when saturated, contain from 1 to 5 per cent of water by weight, and this corresponds to a pore space of about 2.5 to 12.5 per cent. The more porous limestones are capable of absorbing 10 per cent or more of water by weight. Sandstones are ordinarily very porous, holding from about 2 or 3 to 15 per cent of water by weight. This corresponds to a pore space of from about 5 to 28 per cent Capacity to hold about 10 per cent by weight, and therefore a pore space of about 20 per cent, is very common in sandstones. The extreme of porosity for sandstones yet reported is the Dunnville sandstone of Wisconsin, which, according to Buckley, contains a fraction more than 28 per cent of air space when dry,[a] and therefore when saturated is capable of having 28 per cent of its volume occupied by water. According to Merrill,[b] chalk may contain as much as 20 per cent by weight of water. Supposing the specific gravity of the chalk to be 2.8, this corresponds to a pore space of about 41 per cent. However, in coherent rocks, pore spaces of more than 25 per cent are rather uncommon.

In unconsolidated rocks where cementation has not taken place at all, and in products of the belt of weathering, the pore space may be even greater than the above amounts. If grains of sand are spherical, of uniform size, and "are arranged in the most compact manner possible, each grain will touch the surrounding grains at twelve points."[c] In this case the pore space will be 25.95 per cent.[d] If the particles be spherical, of uniform

[a] Buckley, E. R., Building and ornamental stones of Wisconsin: Bull. Wisconsin Geol. and Nat. Hist. Survey, No. 4, 1898, p. 225.

[b] Merrill, G. P., Rocks, rock-weathering, and soils, Macmillan Co., New York, 1897, p. 198.

[c] Slichter, C. S., Theoretical investigation of the motion of ground waters: Nineteenth Ann. Rept. U. S. Geol. Survey, pt. 2, 1899, p. 306.

[d] Slichter, cit., p. 310. Becker, G. F., Geology of the quicksilver deposits of the Pacific coast: Mon. U. S. Geol. Survey, vol. 13, 1888, p. 399.

size, and arranged "so that the lines joining their centers form cubes,"[a] this will be the most open possible arrangement. In this case the pore space will be 47.64 per cent.[b]

King has made a number of experimental determinations of the pore space of unconsolidated sands, of broken rocks, and soils, the material being packed as closely as he was able to pack it.[c] Where quartz sand comprising materials varying greatly in coarseness was used, a pore space as low as 25.43 per cent was obtained.[d] But "well-rounded grains of nearly uniform diameter tend to give a pore space which lies between 32 and 40 per cent. * * * For simple sands with angular grains the pore space is much larger than it is for the rounded sands of the same size of grains, and in the case of the crushed glass, whose grains are more angular than those of the crushed limestone, which have a tendency to be cuboidal in form, the pore space is the largest of all."[e]

Seelheim found that clays when allowed to settle in water have a pore space of 50 to 79 per cent, and that there is no sensible reduction of this space under a pressure of 30 meters of water.[f]

In clay loams and clays pore spaces as high as 48 to 52 per cent were obtained by King.[g] He suggests that the high pore space of clays may possibly be partly explained by the angularity of the grains, it being well known that the very fine mechanical sediments are largely composed of angular particles.[h]

It is evident from these experimental results of King's that the grains of sands and soil are not packed by nature in the most compact manner possible; otherwise the pore spaces would run lower, rather than higher, than Slichter's minimum pore space (25.95 per cent); for the natural grains

[a] Slichter, cit., p. 308.

[b] Slichter, cit., p. 309.

[c] In order to get the closest packing, the material was added "in small lots at a time and gently tamped with a broad, flat-faced pestle until the vessel was filled. . . . The vessel, after being filled by tamping, was 'struck off' with a piece of plate glass, then held firmly while with light blows the walls of the tubes were struck gently, but repeatedly, as long as any reduction in volume could be produced."—King, F. H., Principles and conditions of the movements of ground water: Nineteenth Ann. Rept. U. S. Geol. Survey, pt. 2, 1899, p. 208.

[d] King, cit., p. 211.

[e] King, cit., p. 215.

[f] Seelheim, Zeitschr. für anal. Chemie, vol. 19, p. 387; cited in King, F. H., Principles and conditions of the movements of ground water: Nineteenth Ann. Rept. U. S. Geol. Survey, pt. 2, 1899, p. 78.

[g] King, cit., pp. 213–215.

[h] King, cit., pp. 217–218.

of soil and sand are not spherical in shape, or of uniform size. In so far as the grains vary from regular forms and uniform magnitude the pore space would be less than calculated; but in so far as the method of packing is not the most compact possible the pore space would be greater than calculated. Thus these two factors neutralize each other to a considerable degree, and we are obliged to turn to experiment to ascertain approximately the facts. It is probable that King's experimental results[a] on sands composed of well-rounded grains of nearly uniform diameters, where the pore space was between 32 and 40 per cent, represent approximately the original pore space in the coarser assorted mechanical sediments. The more porous sandstones, where the pore space, as ascertained by Buckley,[b] varies from 18 to 28 per cent, have a crushing strength varying from 172 to 413 kilograms per square centimeter; indeed, are strong enough to serve for building stones. It is clear that a considerable amount of cementing material has been added, and that the pore space measured is much less than the original space in the sands before cementation. Hence it appears, both from experimental work by King and by deductions from actual measurements of the space in partially cemented sandstones, that the original pore space in clean, well-assorted sands probably varies from one-fifth to as much as two-fifths, with a probable average of about one-third.

It is much more difficult to give a statement as to the average pore space of the lavas. Some of these rocks are rather dense and had originally a very small amount of pore space; others are exceedingly vesicular and originally had pore spaces amounting to 50 to 75 per cent, or even more. It is rather probable that where a succession of thin-bedded basic lavas are piled up one on the other, as in the Keweenawan of the Lake Superior region, the pore space averages as much as in ordinary sandstones; but from this maximum the average runs down as the lava flows become thicker and as they become more acid. Therefore the average pore space of the vesicular lavas is probably not more than one-third to one-half as great as in the mechanical sediments.

It is even more difficult to make an estimate of the amount of pore space due to fractures in the rocks, such as faults, joints, fissility, the open-

[a] King, cit., pp. 147–157.

[b] Buckley, E. R., Building and ornamental stones of Wisconsin: Bull. Wisconsin Geol. and Nat. Hist. Surv. No. 4, 1898, pp. 393–395, 402–403.

ings of autoclastic rocks, etc. In the case of some breccias the pore space is certainly as large as in the mechanical sediments, and such breccias in some places are present in considerable volume. From this maximum amount the pore space of course varies to a fraction of 1 per cent.

I am therefore wholly unable to give any general averages of the amount of pore space, taking the world as a whole. But Shaler has estimated that the amount of igneous and vein material of certain regions of the New England coast is from 3 to 5 per cent of the superficial area.[a] Since the volumes are as the cubes of the dimensions, if the amount of vein material were the same in other directions this would involve a filled pore space of from 0.52 to 1.12 per cent.

From the foregoing it is plain that, while it is easy to ascertain the amount of pore space in a given rock, it is very difficult indeed to make any estimate of the average amount of pore space in the zones of katamorphism and anamorphism. It is shown on pages 187–191 that these zones correspond, respectively, to the zones of fracture and flowage. It is certain that the pore space in the zone of fracture is far greater than in the zone of flowage. It is also equally certain that the pore space in the belt of weathering is vastly greater than in the belt of cementation. When these various zones and belts are discussed it will be shown that both the unconsolidated materials and the coherent rocks of the belt of weathering are exceedingly open and have a very large pore space. It will further be seen that in passing downward from the belt of weathering to the belt of cementation there is a sudden diminution in the amount of pore space available, the rocks becoming almost at once far less open. Doubtless on the average the amount of pore space in the belt of cementation steadily diminishes from the upper to the lower part; and in the zone of anamorphism the pore space is almost certainly but a fraction of 1 per cent.

It is to be remembered that below the comparatively thin belt of weathering, the rocks, with unimportant exceptions, are saturated. Dana estimates the average amount of water contained in the rocks as 2.67 per cent of their weight.[b] Supposing that the specific gravity of the crust is 2.7, this would mean a pore space of 6.89 per cent of the volume of the rocks; or, if the rocks were saturated, about 69 liters of water in every cubic

[a] Shaler, N. S., The crenitic hypothesis and mountain building: Science, vol. 11, 1888, p. 281.
[b] Dana, J. D., Manual of geology, American Book Co., 4th ed., 1895, pp. 205, 311.

meter. Supposing the pore space for the upper part of the zone of fracture to be one-fifth of that suggested by Dana and to diminish to zero at the lower part of that zone, this would give an average pore space for that zone of 0.69 per cent. Supposing that the zone of fracture extends to a depth of 10,000 meters and that the pore space is saturated, the amount of contained water, if concentrated to the exclusion of rock, would make a sheet 69 meters thick, extending throughout the continental areas. This calculation is of course made upon an hypothetical basis (see pp. 569–571), but it shows that the underground water is truly a great subterranean sheet. This subterranean sheet may be compared to the blood of an organism, and the comparison has force to the degree that it is the chief medium through which the transformations of the rocks are accomplished.

CIRCULATION OF GROUND WATER.

Subterranean water must be considered from two points of view—its circulation and its work.

The actual ground-water circulation depends upon the openings in the rocks, the forces producing water circulation, and the forces opposed to circulation.

OPENINGS IN ROCKS.

The rate and amount of flowage of water is largely dependent upon the openings in rocks. The openings in rocks in reference to flowage need to be considered from the following points of view: The form and continuity of the openings, the size of the openings, and the percentage of openings, or pore space.

FORM AND CONTINUITY OF OPENINGS.

For a given cross section, in proportion as an opening approaches a circular form—that is, as it approaches a minimum of wall area per unit of volume—the flow increases, because the friction between the moving water and the film of fixed water upon the walls is less per unit volume. In proportion as the openings are continuous in rocks the flow increases.

The openings in rocks include (1) those which are of great length and breadth as compared with their width, and thus are essentially flat parallelopipeds; (2) those in which the dimensions of the cross sections of the openings are approximately the same, and therefore resemble tubes of various kinds; and (3) irregular openings.

(1) The openings which have great length and breadth as compared with their width are those of bedding partings, of faults, of joints, and of fissility. It is recognized that many of the fractures are exceedingly complex. They are, indeed, in many instances a series of parallel or intersecting fractures, forming a zone of brecciation. However, for such a a zone, as a whole, the statement still holds that the openings have great length and depth as compared with their width.

Bedding partings are parallel to the layers. Since ground waters very frequently follow formations, the bedding partings become important factors in the promotion of flowage parallel to the formation This is especially true of the contacts of formations of different character. These contacts are places of maximum differential movements, of consequent complex fracturing, and therefore of important openings and large circulation.

In position the fault, joint, and fissile openings ordinarily have an important vertical element, or at least traverse the beds. Frequently they are nearly vertical, or traverse layers or formations at right angles. In consequence of this they are very important factors in the vertical movements of ground water.

As to continuity, bedding partings are likely to be the most continuous; faults come next in continuity, joints next, and fissile openings are those that are least continuous.

Bedding partings are likely to be continuous for long distances, and because of this and their size (considered on pp. 137–138), they are frequently important factors in the flowage of ground water.[a]

Faults may have very great continuity. Thrust faults of 15 kilometers and more along the dip are known; and along the strike faults may extend for even hundreds of kilometers, although ordinarily their extent is much less. From their great persistence and from the fact that they are likely to cut across formations, thus frequently severing and displacing impervious strata and consequently connecting porous strata separated by impervious strata with one another, faults are of very great consequence in the flowage of ground water.

Joints are less extensive than faults, but they may extend across an entire formation, or even across two or more contiguous formations. The

[a] King, F. H., Principles and conditions of the movements of ground water: Nineteenth Ann. Rept. U. S. Geol. Survey, pt. 2, 1899, p. 126.

extent of joints along the strike may be many kilometers. While joints are less extensive than faults, they are far more numerous. Probably their number, as compared with faults, more than compensates for their lack of extent. Joints are therefore of very great importance in the flowage of ground water. On the average they may be of even greater importance than faults. Joints, like faults, may connect separated porous strata, but very frequently the joints do not pass through the relatively plastic separating impervious strata, and therefore in this respect are of less consequence than faults.

Fissility openings usually have less extent than bedding partings, faults, or joints; and the openings are small. While they doubtless have an important influence in water flowage, they are not of such consequence as bedding partings, faults, or joints.

(2) Openings in which the dimensions of the cross sections are approximately the same are those of the mechanical deposits, including conglomerates, sandstones, soils, tuffs, etc.

The openings of mechanical sediments have a strong tendency to a definite form, and are continuous. The forms of these openings have been fully discussed by Slichter.[a] The openings alternately narrow and widen. At the wider parts their sections are roughly polygonal, the polygons having more than three sides, and these curved. At their narrowest places the cross sections of the openings approximate triangles, and where the grains are of equal size the triangles are equilateral. The form of the tubes at their minimum is due to the contact of three grains in a plane, the space between which is nearly triangular. (Fig. 3.)

Professor Slichter has further shown that there are various possible natural systems of packing of particles. In nature one system of packing may hold for a certain distance, and then be replaced by another system. Within any system of packing all the openings are connected with one another by straight or curved tubes, triangular at their minimum cross section, and no opening is shut off from any other opening. Slichter has shown that in the various natural systems of packing of the particles there is at least one direction in which the tubes are straight; in other words, there is one direction in which a straight wire may be thrust without coming

[a] Slichter, C. S., Theoretical investigation of the motion of ground water: Nineteenth Ann. Rept. U. S. Geol. Survey, pt. 2, 1899, pp. 305–323.

in contact with any grain. (Fig. 4.) In any other than the one direction, where the grains are naturally arranged, the tubes are ordinarily interrupted. In any case the continuity of the tubes in straight lines persists so far as the arrangement of grains is by one system of piling. Slichter has shown that the openings in the directions in which the tubes are not straight may be neglected so far as the flowage of water is concerned; he therefore concludes the quantity of flowage to be dependent upon the continuous straight or nearly straight tubes. These of course vary in size, but the water may be reckoned as passing through continuous tubes of the minimum size, made by the cross section between three grains arranged in a plane at right angles to the direction of the tubes. Of course it is understood that any

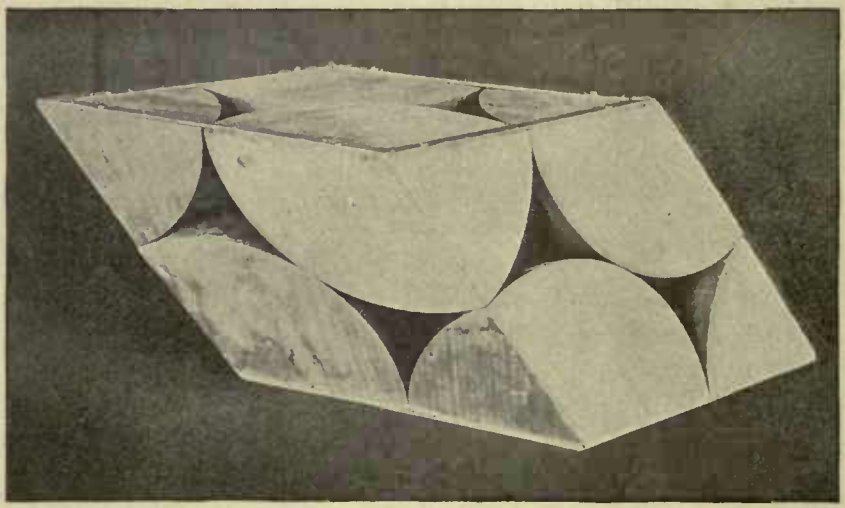


FIG. 3.—Triangular cross sections of pore space. After Slichter,

one system of arrangement does not extend indefinitely, and that where one system of packing changes into another there are, ordinarily, bends in the tubes.

Slichter further shows that the amount of space in mechanical sediments before cementation takes place is largely dependent upon the system of packing. It is also dependent upon the regularity of the grains and their variation in size. The more nearly spherical the grains and the more nearly uniform the size, the greater is the pore space.

Ordinarily the continuous tubes of mechanical sediments are limited by the boundaries of a stratum or formation. However, a porous formation may extend for hundreds of kilometers and have a thickness of hundreds

of meters. This is well illustrated by the strata bearing artesian water, many of which certainly transmit great quantities of water for hundreds of kilometers. An excellent illustration of porous strata of this class is the Dakota sandstone. This sandstone yields great quantities of water along the James River Valley, and the nearest feeding area, so far as known, is in the Black Hills, 400 kilometers distant. The volume of water which issues

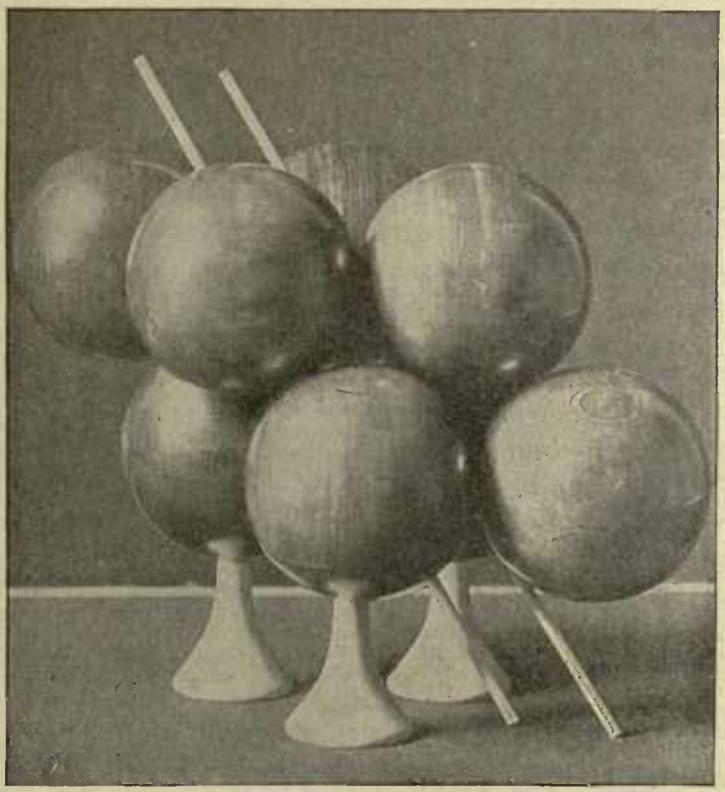


FIG. 4.—Spheres packed in the most compact manner possible, showing continuous openings in one direction. After Slichter.

from sandstone strata in artesian basins shows how important is the class of openings under consideration.

Since the continuous openings of sediments are commonly limited to a formation, it is plain that such openings are very favorable to the flowage of water along a formation, but are less potent in the transference of water from one stratum or formation to another.

(3) Irregular openings are those of the vesicular lavas and of the

irregular fractures of rocks. In rocks where the openings are exceedingly irregular in form the flowage of water is limited by the continuous openings, however small they may be.

Irregular openings may be of any form. In the lavas they are frequently spherical or ovoid. In the compact rocks they are confined to the very minute, exceedingly irregular interspaces between the mineral particles, which apparently are in perfect contact. As already seen, in the very vesicular lavas the pore space may vary from a small per cent to a very large amount, even to 75 per cent or more. The openings are more likely to be continuous where the pore space is large than where it is small. But even where the pore space is very large the openings of lavas are not nearly so continuous nor the minima of the tubes so large as in sands. In the igneous rocks and in the rocks metamorphosed under deep-seated conditions the openings are minute; they are controlled by the form of the grains. They are, therefore, very irregular and discontinuous.

SIZE OF OPENINGS.

The size of the openings is very important in the circulation of ground water. The size of openings must be discriminated from the amount of pore space. The amount of pore space may be the same in two cases, but in one the openings may be very few and large, and in the other very numerous and small. The flowage in the two cases, other conditions being equal, is very different. For a given mass of water the internal friction, both within the moving water and between the moving and fixed water increases very greatly as the openings decrease in size. It is, therefore, necessary to consider the various classes of openings in reference to size.

Upon the basis of size openings in rocks may be divided into (a) openings larger than those of capillary size, or supercapillary openings; (b) capillary openings, and (c) openings smaller than those of capillary size, or subcapillary openings.

For water, openings larger than capillary openings, according to Daniell,[a] may be circular tubes which exceed 0.508 mm. in diameter, or may be sheet openings, such as bedding partings, faults, joints, etc., the widths of which exceed one-half of this, or 0.254 mm. To movement of water in such

[a] Daniell, Alfred, A text-book of the principles of physics, 3d ed., Macmillan Co., New York, 1895, pp. 315–317.

openings the ordinary laws of hydrostatics apply. Capillary openings for water solutions include those which, if circular tubes, are smaller than 0.508 mm. in diameter, and those which, if sheet spaces, are narrower than 0.254 mm., and which in either case are larger than the openings in which the molecular attractions of the solid material extend across the space. Such openings in the case of circular tubes are those smaller than 0.0002 mm. in diameter, or, if sheet passages, are below 0.0001 mm. in width. Capillary openings, therefore, include circular tubes from 0.508 to 0.0002 mm. in diameter, and sheet passages from 0.254 to 0.0001 mm. in width. Capillary openings of other forms have a range limited between 0.508 and 0.0001 mm., but no one form has so wide a range as this. To movement of water in openings such as these the laws of capillary flow apply. By subcapillary openings are meant those in which the attraction of the solid molecules extends from wall to wall. These include all tubes smaller than 0.0002 mm. in diameter, and sheet openings smaller than 0.0001 mm. in width. For intermediate forms the subcapillary openings have as their maximum limit a range from 0.0002 to 0.0001 mm.

It is not supposed that supercapillary openings, capillary openings, and subcapillary openings are sharply separated from one another. They grade into one another, and the laws below given which control the flowage in one class of openings are gradually modified until they pass into the laws which control the flowage in another class of openings. For instance, water in circular tubes slightly larger than 0.508 mm. in diameter would to some extent obey the laws of flowage of capillary openings, and water in tubes slightly less than 0.508 mm. in diameter would to some extent obey the laws of supercapillary flow. In short, flowage in openings near the dividing line between two classes obeys laws intermediate between those controlling flowage in the typical cases of each class.

The areas of openings of variable size and similar form vary as the squares of their respective diameters. The circumferences of openings of variable size and similar form vary as their respective diameters. It follows, for a given volume of water, that the larger the openings in which it is contained the less is the surface of contact. For instance, if for an opening of any form, of given diameter, the surface of contact for 1 cm. of length be 1 sq. cm., if the cross diameter be doubled, the length remaining the same, the volume of the water is four times as great, but the surface of

contact is only twice as great. If the diameters be decreased to one-third, the volume of the water is decreased to one-ninth, but the surface of contact to one-third only.

As a consequence of the relation between size of openings and area of contact, it follows that in small openings a given volume of water is capable of performing much more work upon the rocks than in openings of larger size, for the surfaces of contact are the places where chemical interaction between the water and rock takes place. How important is the factor of small size in the amount of work which may be accomplished by ground water can be adequately comprehended only when the surface of action for a given volume of water for small openings is calculated. To illustrate, if the openings are circular tubes of a size at the border line between those of supercapillary and capillary size—that is, tubes 0.508 mm. in diameter—1 cu. cm. of water would have a surface contact with the rocks of about 78.74 sq cm. If the openings be sheet openings at the boundary between supercapillary and capillary—that is, 0.254 mm. in width—1 cu. cm. of water would have a surface contact of about 78.74 sq. cm. If the openings be circular tubes at the border line between those of capillary and subcapillary openings—that is, 0.0002 mm. in diameter—1 cu. cm. of water would have a surface contact of about 200,000 sq. cm. If the openings be sheet openings at the border line between those of capillary and subcapillary size—that is, have a width of 0.0001 mm.—1 cu. cm. of water would have a surface contact of 200,000 sq. cm. Therefore 1 cu. cm., or 1 gram of water, has a surface contact varying from 0.007874 to 20 square meters in circular capillary tubes; and in sheet passages has a surface contact varying from 0.007874 to 20 square meters. It has been calculated by Whitney that "the grains in a cubic foot of soil have, on the average, no less than 50,000 square feet of surface area."[a] The magnitude of these numbers shows how important a factor in the work of a given volume of ground water is the size of the openings in which the water is contained.

It follows from the above relations that the area of contact, and therefore the friction between moving water and the fixed film of water adherent to the walls, is inversely as the size of the openings. As will be

[a] Whitney, Milton, The physical principles of soils in their relations to moisture and crop distribution: Bull. Weather Bureau No. 4, U. S. Dept. of Agric., 1892, p. 14.

seen, this is a matter of controlling consequence in flowage in small and especially in very small openings.

Supercapillary openings.—The flowage of water through supercapillary tubes is controlled by the ordinary laws of hydrokinetics. Ignoring friction, the flowage of water is as the square root of the pressure or head. If V=velocity, H=head, and G=force of gravity, then V per second $=\sqrt{2GH}$. For instance, the velocity resulting from a pressure of 1 atmosphere or a head of 1033.3 cm. would be the square root of $2 \times 981 \times 1033.3 = 1423.8$ cm. per second.[a]

This formula is only approximately correct, for the internal friction in supercapillary tubes is dependent upon the viscosity of the solutions, upon the regularity of the openings, upon their length and size, and upon the velocity of flowage. If the openings be not straight, or vary in size, or both, eddies form, which increase the internal friction and decrease the speed of movement. The friction between the moving liquid and that fixed to the walls increases with increase of length, with decrease of size, with roughness of surface, and with increase in velocity. If the available area be great and the movement consequently very slow, the resistance per unit of length due to friction becomes so small as to be almost inappreciable. But even if the openings be large and continuous the formula gives somewhat too high results. If the flow be rapid in long, rough, irregular underground passages, the resistance is so great as to make the formula above given inapplicable.

Supercapillary openings include the greater number of bedding partings, fault openings, joint openings, some of the openings of fissility, and the openings in the coarser mechanical sediments, such as coarse sandstones and conglomerates. The distance from an angle to the opposite side of the roughly triangular tubes (fig. 3, p. 132) in sandstones composed of spherical grains of equal size, which average 3 mm. in diameter, somewhat exceeds 0.508 mm.[b] The average diameter of the pores in the system of closest packing is 43 per cent greater than the minimum section of the triangular pores.[c] It therefore follows that a sediment composed of grains just large

[a] Daniell, Alfred, A text-book of the principles of physics, 3d ed., Macmillan Co., New York, 1895, p. 303.

[b] Slichter, C. S., Theoretical investigation of the motion of ground water: Nineteenth Ann. Rept. U. S. Geol. Survey, pt. 2, 1899, p. 316.

[c] Slichter, cit., p. 317.

enough to make the pores capillary at the smallest section have supercapillary pores in other parts of the section. Hence, it may be said that sandstones and conglomerates the grains of which exceed 3 mm. in diameter have tubes which are greater than those of capillary size. But the grains in the great majority of sandstones average less than 3 mm. in diameter, and hence the pore openings in sandstones are for the most part capillary, and are considered under the next heading.

It is through openings exceeding those of capillary size—that is, circular tubes larger than 0.508 mm. in diameter and sheet openings greater than 0.254 mm. in diameter—that the rapid circulation of underground water is accomplished. For instance, the openings through which springs of large size issue mainly exceed those of capillary dimensions.

Capillary openings.—Capillary openings include the great majority of the openings of sands and sandstones, many of the openings of fine conglomerates, many of the openings of porous lavas, and many of the openings produced by fracture. As already noted, the superior limit of size of grains of sands and sandstones composed of grains of uniform size, the smallest openings of which are capillary, is 3 mm. in diameter. The inferior limit of size are grains, the diameters of which are six times the maximum diameter of subcapillary tubes, or 0.0012 mm. The majority of the particles of most clays, shales, and slates are much smaller than this, and therefore the openings of these rocks are subcapillary. Hence capillary openings in mechanical sediments range from very fine sands to very coarse sands. Many of the openings of fissility are capillary; but the majority of bedding partings, fault openings, and joint openings are partly supercapillary, although often the walls of such fractures are so close together as to make even these openings capillary in part.

In capillary openings the resistance to flow increases very rapidly as a tube diminishes in size. This is due to the fact, already explained, that the area of contact between the moving liquid and that fixed to the wall increases inversely as the size of the openings. Indeed, the friction between the moving and the fixed liquid becomes the dominant factor in the resistance to flowage in capillary tubes. As openings decrease in size, at the diameter at which this factor controls for a given liquid the openings become of capillary size for that liquid.

According to Poiseuille, the general formula for the flow through a tube of circular section is

$$f=\frac{\pi a^4 p}{8\mu l},$$

in which f is the discharge in cubic centimeters per second, a is the radius of the tube, l its length, p is the difference in pressure at its ends in dynes per square centimeter, and μ is the coefficient of viscosity of the liquid.[a] According to Slichter, "if A is the area of cross section, this formula may be written

$$f=\frac{A^2 p}{8\pi\mu l}$$

and the mean velocity of the fluid in the tube is given by

$$v=\frac{pA}{8\pi\mu l}=(0.03979)\frac{pA}{\mu l}"[a]$$

In a triangular tube the flow per second is represented by the formula

$$f=\frac{pA^2}{20\sqrt{3}\,\mu l}$$

and the velocity by the formula

$$v=(0.02887)\frac{pA}{\mu l}$$

"The mean velocity for a circular tube of equivalent area of cross section was found to be about 38 per cent more."[b] Slichter finds the volume and velocity of flow in an elliptical cylinder to vary but slightly from that of a circular tube. "Even an eccentricity of 0.866 will change the flow by but 10 per cent, and an eccentricity of one-half will reduce the flow by about one-half of 1 per cent. Thus it is clear that a slight change in the shape of the cross section of a tube will change but slightly the flow through it. Analogy warrants us in extending this truth to tubes having other than elliptical sections. For example, we may conclude that the flow through a tube whose section is an oblique triangle is given approximately by the formula for a tube whose section is an equilateral triangle of the same area, even though the shape of the section of the given tube differs slightly, or even materially, from that of an equilateral triangle."[b] Further-

[a] Slichter, C. S., Theoretical investigation of the motion of ground water: Nineteenth Ann. Rept. U. S. Geol. Survey, pt. 2, 1899, p. 317.

[b] Slichter, cit., p. 319.

more, in capillary tubes "the velocity of flow through a tube of variable section will be less than the velocity of flow through a tube having a uniform section equal to the mean section of the first tube, because of the viscosity or internal friction of the expanding or contracting stream."[a]

Daniell expresses a part of the laws of capillary flow in words, instead of in a formula, as follows: "The flow in capillary tubes is proportional not to the square, but to the fourth power of the radius; the velocity is proportional not to the square root of the pressure, but to the pressure itself. The resistance in capillary tubes varies directly as the velocity; in wide tubes approximately as the square of the velocity. This seems discrepant; but it is due to the formation of eddies in the wider tubes; in a capillary tube the flow is steady."[b]

From the foregoing it follows that the flow in a tube with a radius one-fifth millimeter in diameter is sixteen times as great as in a tube one-tenth millimeter in diameter. Furthermore, in a tube of any definite length, if the pressure be doubled the flow is doubled; if trebled the flow is trebled, etc. However, experimental work by King upon the flowage of water through capillary openings of sandstones and sands gave results showing that under the conditions in which he performed his experiments the flowage increased faster than the pressure. The pressure in the experiments varied from a small fraction of an atmosphere to somewhat more than an atmosphere. The departure from Poiseuille's law varied from less than 1 per cent to more than 50 per cent.[c] In the experiments the departures seemed to be greater, on the average, when very low pressures were used than when moderate pressures were used. The very variable results may be partly explained by the conditions under which the experiments were performed, but it is entirely possible that the departures are partly to be explained by the relative importance of internal friction due to viscosity when the rates of movements are slow. (See pp. 141–143.)

Also, according to Poiseuille's law, the flowage is inversely as the viscosity. When it is remembered that the viscosity of water decreases rapidly with increase of temperature, it is seen that this is a very important

[a] Slichter, C. S., Theoretical investigation of the motion of ground water: Nineteenth Ann. Rept. U. S. Geol. Survey, pt. 2, 1899, p. 320.

[b] Daniell, Alfred, A text-book of the principles of physics, 3d ed., Macmillan Co., New York, 1895, p. 316.

[c] King, F. H., Principles and conditions of movements of ground water: Nineteenth Ann. Rept. U. S. Geol. Survey, pt. 2, 1899, pp. 135–157.

factor. The relative viscosity of water at various temperatures below 100° C. is as follows:[a]

Relative viscosity of water at different temperatures.

0°	100.00
15°	63.60
30°	44.90
45°	33.89
60°	26.94
75°	21.75
90°	18.16

From this table it appears that the viscosity of water at 45° C. is about one-third its viscosity at 0° C.; at 90° C., less than one-fifth as great as at 0° C. It therefore follows that temperature is a factor of the greatest importance in the flowage of water through capillary openings in the lithosphere. It is shown (pp. 138, 145–146) that the openings in the lithosphere are largely those of capillary or subcapillary size; hence the importance of the temperature element.

Another factor entering into the flowage of ground water is the influence of the meniscus where the openings are not fully occupied by water. Wolff[b] has shown that if water be introduced into an empty capillary tube, the meniscus in advance of the column is an important retarding influence, and consequently that the movement is slower than under circumstances where there is no meniscus. This influence is likely to be important in many cases in the belt of weathering, where partial filling is the rule, but is probably of little consequence in the belt of cementation below the level of ground water, where saturation is the rule.

In conclusion, it should be fully understood that the laws of capillary flow, as developed by Poiseuille and others, involve rather rapid movement through the capillary openings. It has already been stated that viscosity of the solutions and friction between the moving and the fixed water are the determinative factors in reference to capillary flow. It is highly probable that where the movements are *very* slow the friction is minute or inappreciable and that the consequent departures from Poiseuille's laws are very great. Apparently in the exceedingly slow movements of many of

[a] Landolt and Bornstein Tabellen, 1894, p. 288; supplemented by experimental data furnished by Mr. C. F. Bowen.

[b] Wolff, H. C., The unsteady motion of viscous liquids: Trans. Wisconsin Acad. Sci., Arts, and Letters, vol. 12, pt. 2, 1900, pp. 552–553.

the larger masses of ground water the viscosity of water and the friction becomes almost zero per unit area. Evidence of this is furnished by the fact that artesian water flowing through rocks for hundreds of kilometers, the openings of which are capillary, may have nearly the full pressure due to head. For instance, the artesian water adjacent to Lake Michigan at Chicago at the early wells, before they became so numerous as to interfere when allowed to flow, had a head of 30 meters above the surface, and the feeding area is only about 80 meters above Chicago;[a] yet the water has traveled underground from 150 to 250 kilometers. The resistance causing the loss of head of 50 meters is to be distributed through this distance; therefore the friction per meter must have approached an infinitesimal amount. The same thing is again finely illustrated by the artesian wells of the James River Valley of South Dakota. The water of these wells must have traveled at least from the eastern border of the Black Hills, 400 kilometers. The elevation at the source is 1,500 meters and at the James River 500 meters. The consequent loss of head of considerably less than 1,000 meters is due to resistance through the entire distance, and again must be almost immeasurably small per meter.[b] In all such instances the average movement is exceedingly slow, for it will be shown that to accomplish the first of the above journeys more than a century was perhaps required, and for the second possibly centuries were necessary. (See pp. 585–586.)

But the moment the speed of movement becomes appreciable the resistance promptly runs up. This is shown by the very slow fall of a slanting water table in sands as the result of lateral flowage. The best illustration of this of which I know is that kindly furnished me by J. B. Lippincott, city engineer, of Los Angeles, Cal. The Los Angeles River is mainly fed by ground waters derived from granitic and other sands which are of moderate coarseness, but the openings of which are capillary. The water table rises from the headwaters of the river to a point north of Fernando—about 16.1 kilometers—from a little more than 180 meters to a little more than 330 meters, or 9.3 meters per kilometer. Mr. Lippincott says that from 1896 to 1900, inclusive, five years, there was practically no rainfall, and

[a] Leverett, Frank, The water resources of Illinois: Seventeenth Ann. Rept. U. S. Geol. Survey, pt. 2, 1896, pp. 805–806, 811.

[b] Darton, N. H., Artesian waters of the Dakotas: Seventeenth Ann. Rept. U. S. Geol. Survey, pt. 2, 1896, pp. 665–670, pl. lxx.

therefore no addition to the ground waters During that time the water table fell in the granitic sand, on an average, at the rate of 0.38 meter per kilometer per annum. This fall of water during these years in the granitic sands alone, Mr. Lippincott says, is sufficient to account for the entire discharge of the Los Angeles River. A head of 9.4 meters per kilometer in large channels where friction is small would result in the outpouring of the great quantity of water held in the gravels into the Los Angeles River in a very short time. But the openings in the sands are capillary, and the resistance due to friction and to viscosity is such that the water was very slowly delivered to the river under a head of 9.4 meters per kilometer, the average fall being, as explained, 0.38 meters per kilometer per annum.

Movement as slow as this must be rapid as compared with the exceedingly slow movement of the ground water in the artesian basins referred to. It follows from these illustrations that the ordinary rates of movement in the belt of cementation are very much slower than were the movements under the conditions in which Poiseuille, King, and others carried on their experiments. It is plain that the laws derived from experiments as given by Poiseuille and King in reference to capillary flow are only very partially applicable to movements of ground water; indeed, their application is probably limited to the somewhat rapid movements of the water in the capillary tubes above the level of ground water in the belt of weathering where gravity has its full effectiveness, and adjacent to large openings, either natural or artificial.

Subcapillary openings.—By subcapillary openings, as already explained, are meant openings smaller than capillary openings. In subcapillary openings the attraction of the solid molecules extends from wall to wall, and therefore in these openings the water is wholly that of the films attached to the walls by molecular attraction. There is no free water, in the sense that the molecules are free to move among themselves, resisted only by the viscosity of the fluid. The ratio of the resistance to movement of water thus attached as films to solids is almost infinitely great as compared with that of free molecules. Water thus attached is as if glued to the walls.

Quincke has determined that the attractive influence of glass upon a fluid extends through a silver film 0.00005 mm. thick; or, stated in another way, he finds that the distance through which molecular attraction acts is

in general 0.00005 mm.[a] Plateau made the distance through which molecular attraction acts $\frac{1}{17000}$ mm.,[b] which amount is slightly greater than Quincke's determination. Since each wall holds a film of water, sheet passages below 0.0001 mm. in diameter are subcapillary. The maximum size for the subcapillary circular openings is twice as great, or 0.0002 mm. in diameter.

The laws of flowage of water through tubes of such small size have not been investigated, so far as I am aware. However, upon theoretical grounds one would expect that the flow would be exceedingly, indeed indefinitely, slow even as compared with flow in capillary tubes. This anticipation is fully justified by the observed facts of geology. It is well known that natural oil and gas may be held in anticlinal arches and domes for long periods of time, even when under great pressure. It is certain in these cases that the escape of oil, or even gas, through the subcapillary openings of the shales is slower than the manufacture of these products in nature's laboratory. The facts as to the retention of oil and gas under shale roofs render it highly probable that flow in subcapillary openings is so slow as to be inappreciable during the time through which an experiment is ordinarily continued; but the flow in subcapillary openings during geological periods is probably of great consequence. (See pp. 892–904.)

It may be anticipated that the slow movement of water in subcapillary openings is greatly influenced by change of temperature. At high temperatures the viscosity of water is an important element in flow, and this rapidly decreases with increasing temperature. That water gas does not obey the law of flow of liquids in subcapillary tubes is shown by the experiment of Daubrée,[c] in which the vapor of water at a temperature of 160° C., and consequently at a pressure of 6 atmospheres, passed through a layer of apparently solid rock 2 cm. in thickness, and gave a pressure on the other side of 1.9 atmospheres. This experiment shows beyond all question that water gas under high pressure and temperature does not adhere to the walls strongly, and has such a small viscosity that it slowly but surely passes through subcapillary openings. However, ground water at all temperatures below the critical temperature under ordinary conditions

[a] Quincke, M., Ueber die Entfernung in welcher die Molecularkrafte der Capillaritat noch wirksam sind: Poggendorff, Annalen, vol. 138, p. 402.

[b] Plateau, J., Statique des liquides, vol. 1, 1873, p. 210.

[c] Daubrée, A., Géologie expérimentale, Paris, 1879, vol. 1, pp. 236–238.

is held by the pressure in the form of a liquid. But at temperatures higher than 365° C., or the critical temperature of water, whatever the pressure, the water is in the form of water gas. In this case it may be supposed to have a much greater penetrating power than in the form of liquid, since it can not be considered as adhering to the walls of the openings.

Even if subcapillary openings be very small and the flow very slow, it does not follow that the water within these minute openings is not an agent through which important geological work is accomplished. The water in such spaces is capable of taking into solution the substances with which it is in contact, of depositing material from solution, of reacting upon the substances by hydration; in short, is capable of performing all the transformations which freely moving water is able to accomplish. Indeed, it has already been seen that all transfers of material between water and rock must take place through the fixed films of water. (See p. 64.) The transfer of material in subcapillary openings is confined to short distances because there is no free circulating water. The interchanges of material are probably slow, except between adjacent or nearly adjacent mineral particles; therefore it seems highly probable that a given volume of water in the subcapillary openings is far more effective in transforming rocks than an equivalent volume in larger openings. The same reasoning applies here as in the case of the capillary openings as compared with supercapillary openings. The surface of action per unit volume in the subcapillary tubes is vastly greater than in larger openings. As shown on pages 686–698, the above conclusion as to the efficacy of water in subcapillary openings is fully justified by the facts. It is there seen that the minute amount of water contained in the subcapillary openings is the medium through which the complete transformation of rocks to schists and gneisses has been accomplished. I therefore conclude that, while it is probable that the actual flow of water and transfer of material in subcapillary openings is comparatively slow, it is certain that most profound alterations of rocks take place through this water as the agent of transformation.

Subcapillary openings include the openings of mechanical sediments the particles of which, if spherical and of uniform size, are not greater than 0.0012 mm. in diameter. As a matter of fact, many of the openings in

which a portion of the particles are larger than this have subcapillary openings, since the larger openings are occupied by grains as small as or smaller than the above dimensions. The great majority of the clays, shales, and slates are largely composed of particles smaller than 0.0012 mm. in diameter and their openings are subcapillary. Minute openings between the grains of the igneous rocks and of the rocks metamorphosed to schists and gneisses are also usually subcapillary. Where practically all of the openings are subcapillary, whether they be the openings of sedimentary, igneous, or metamorphic rocks, such rocks constitute practically impervious strata; for the contained water is in fixed films held by molecular attraction, and the circulation, as already explained, is so slow as to be negligible during short time intervals.

PERCENTAGE OF OPENINGS, OR PORE SPACE.

The percentage of openings in the rocks, or the pore space, is a function of the number and the size of the openings. In so far as the openings in rocks are large and numerous, there is a large pore space. It has already been seen (pp. 124–129) that the absolute amount of openings in rocks, as shown by observation, varies from a small fraction of 1 per cent to over 50 per cent. The larger the pore space the more favorable the conditions for circulation, but since the variation in pore space is so great it is evident that the flowage of water dependent upon porosity is very variable. Water passes readily through rocks which contain much pore space; water does not flow to an appreciable extent through rocks which have a small fraction of 1 per cent of pore space. *Other factors being the same, and the pore space of the same character, the flowage is in direct ratio to the amount of pore space.*

FORCES PRODUCING WATER CIRCULATION.

The forces producing circulation of ground water are gravity, heat, mechanical action, molecular attraction, and vegetation. The dominant force, upon which the movement of ground water mainly depends, is gravitative stress.

Gravity.—Gravity ever tends to pull the water downward. And this never-ceasing force at work throughout the zone of water circulation, on the average continuously carries the circulating water to lower levels. This condition of affairs is analogous to the work of gravity in earth movements.[a]

[a] Van Hise, C. R., Earth movements: Trans. Wisconsin Acad. Sci., Arts, and Letters, vol. 11., 1898, pp. 465–516.

But in earth movements and water circulation alike, all the elements of the movement must be taken into account. The downward movement of a greater mass of earth or water may result in the upward movement of a lesser mass. The upward movements of water dependent upon downward movements of other water are of relatively greater importance in the water circulation than are the upward movements of rocks consequent upon downward movements of larger masses of material in earth movements.

Indeed, it will be seen that commonly the circulation of a system of ground water in the belt of cementation involves both downward-moving and upward-moving masses. In such systems of ground-water circulation gravity is effective in the movement in proportion to the head. Head is due to the fact that the water entering the ground at a certain level, after a short or long underground journey, issues at a lower level.

Also where there is a difference in the density of the two columns due to difference in the amount of material held in solution, gravity promotes circulation independently of head, the column holding more salts being pulled down and the lighter column driven upward. Probably the amount of material in solution is usually not so great as to make this an important factor in the process, but in salt regions it may be important. The density of the water of the sea as compared with fresh water is 1.02765 to 1.02795,[a] and the density of a saturated solution of sodium chloride at 4° C., as experimentally determined by Mr. S. H. Ball, is 1.2063. Of course in actual cases such differences as these are not found, for both columns are sure to have salts in solution; but where springs empty under the sea the first case is approached. In such instances, the increased density of the sea water opposes the head of the lighter stream of relatively pure water.

Heat.—Change in temperature may result in the expansion and contraction of water, and such changes in volume necessarily involve some movement. The volume of water varies as the temperature. Taking the volume of water at 4° C. as 1, its volume at 50° C. is 1.0120, at 75° C. is 1.0258, and at 100° C. is 1.0432.[b] Therefore the increase in the temperature of underground water may increase its volume and lessen its density as much as 4 per cent without exceeding its boiling point at atmospheric pressure, and a difference in the density of two columns by 1 per

[a] Bischof, Gustav, Elements of chemical and physical geology, translated by Paul and Drummond, Harrison & Sons, London, vol. 1, 1854, p. 97.

[b] Austin, L. W., and Thwing, C. B., Exercises in physical measurements, Allyn & Bacon, Boston, 1895, p. 151.

cent or more is probably not uncommon. Decrease in temperature may correspondingly increase the density of water.

Gravity and heat.—While change of temperature necessarily involves some movement, its chief effect in water circulation is as a force subordinate to gravity. In so far as water in a connected descending and ascending system is warmer at its point of issuance than it was when it joined the sea of underground water, this gives gravity an effect in circulation in the same direction as head. This is consequent upon the fact, noted above, that the density of water varies inversely with the temperature.

It is therefore evident that in columns of water of equal length the stress of gravity is greater upon the column having the lower temperature. That the diffence in gravitative stress due to difference in temperature may be sufficient to produce rapid circulation in pipes that are supercapillary is shown by the use of the principle in the hot-water system of heating buildings. Underground, as in the hot-water system of heating, heat is the energy which causes the water to expand, and gives a difference in density. When heat has produced a difference in density of the two columns, gravity is the force which inaugurates and maintains the circulation.

It is believed that underground circulation may be promoted to an important extent by difference in temperature of the descending and ascending columns of water, resulting from heat abstracted from the rocks due wholly to their normal increment of temperature with depth. Later it will be shown that the downward-moving water is ordinarily dispersed in many small openings and moves relatively slowly; therefore it may be supposed at any given place to have approximately the temperature of the rocks. The upward movement of water, on the contrary, is shown to be usually in the larger openings and relatively rapid; therefore at any given place its temperature is probably higher than is normal for the rocks at that depth. The result is a difference in temperature between the descending and ascending columns, the ascending column being the warmer.

In regions where volcanism, or mechanical action, or both, have recently occurred, the difference in density resulting from difference in temperature between the descending and ascending columns is likely to be a much more important influence in the circulation of the ground waters than in regions where the difference in temperature is due to the normal heat of the rocks. Such a region is the Yellowstone Park.

In some countries the issuing waters throughout great regions are very clearly at a higher temperature than the entering waters, and in such regions the difference in temperature must be a very important factor in the underground circulation. In such cases the difference in temperature between descending and ascending waters generally results from a combination of the normal increase of temperature due to depth, from regional volcanism, and from the rocks having a higher temperature than normal because of recent orogenic movements. An excellent illustration of such regions is the Cordilleran region of western United States. (See pp. 591–592.)

As already noted, the expansion of water with increase of temperature is considerable, amounting to over 4 per cent between 0° and 100° C.; that is, a given mass of water occupies a volume 4 per cent greater at the latter than at the former temperature. In other words, if there be an average difference of 100° C. between the ascending and descending columns, 100 meters of the downward-moving water balances 104 meters of the upward-moving water. If we suppose the descending and ascending columns to be connected, of equal height, and having an average difference in temperature of 100° C., this would be equivalent to a head of 4 meters per 100 meters for the entire height of the column. Probably the difference in temperature between two columns is not often so great as 100° C., but if it be sufficient to give a difference in density of 1 per cent, and the ascending and descending columns be the same length, this is ample to give a stress sufficient to overcome friction and viscosity, and give a decided movement to ground water. As an illustration of the principle may be mentioned the water power of the sea mills of Cephalonia, which, according to the Crosbys, is wholly due to difference in temperature between the descending and ascending waters.[a]

Mechanical action.—A third force influencing ground-water circulation is mechanical action. Earth movements may close or partly close the openings in the rocks, and in this process squeeze out the water, as in the production of the schists and gneisses from the sedimentary rocks. If the deformation of the rocks be referred to their ultimate cause, gravity, even the circulation of the water resulting from deformation is indirectly due to the stress of gravity.

[a] Crosby, W. F., and Crosby, W. O., The sea mills of Cephalonia: Tech. Quar., vol. 9, 1896, pp. 6–23.

Molecular attraction.—The fourth force affecting the movement of ground water is molecular attraction. This attractive force works between the particles of water themselves (cohesion) and between the particles of water and rock (adhesion).

As a result of molecular attraction water may rise against gravity in capillary or hair-like openings, thus saturating the rocks at higher altitudes than it would were it not for this cause; it may creep along the walls of the openings of rocks without extending from wall to wall, and therefore without saturating the rocks.

The rise of water when it fills capillary openings raises the free surface of water above the normal level. This rise of the free surface is explained by the attraction between the water and the walls, and the attraction of the molecules of water for one another. The strong attraction between the surfaces of mineral grains and water has already been alluded to. As a result of this, water tends to rise along a wall or tube. This is dependent upon the fact that there is greater attraction between the molecules of rock and water (adhesion) than between the molecules of water themselves (cohesion). However, the molecular attraction between the particles of water is very great. The strength of the surface tension of a film of pure water is dependent upon cohesion, and is 81.96173 dynes per square centimeter.[a] When a molecule is surrounded on all sides by free water the attractions in the various directions equalize one another, and so particles are comparatively free to move However, at the surface the upward component of the attraction is zero; hence there is effective tangential and downward attraction. The rise of the water along the walls is due to adhesion. As a result of this attraction a film of water is drawn along the walls. Because of the attraction of cohesion the film of adherent water draws up the next row of molecules away from the walls; these molecules in turn exert an attractive force on the next adjacent molecules, and so on. The attractive force of the surface film of water for the water below draws up the molecules constituting it; this in turn acts upon the film below, and so on. The total effect of the molecular attraction between the walls and

[a] Daniell, Alfred, A text-book of the principles of physics, 3d ed., Macmillan Co., New York, 1895, pp. 271–279. Ostwald, W., Outlines of general chemistry, translated by James Walker, 3d ed., Macmillan Co., New York, 1895, pp. 107–111. Barker, Geo. F., Physics, Holt & Co., New York, 1892, pp. 200–211.

the water and the molecular attraction between the particles of water is to produce an elevation above the normal surface of the water, the upper surface of which is of a shape as though it were an elastic membrane adhering to the walls and being stretched by the weight of the water above the ordinary level below.

The height to which water rises above this natural level is indirectly as the diameter of the capillary openings. In circular glass tubes 1 mm. in diameter, at 20° C., pure water rises 3.32 cm.[a] Between plates 1 mm. apart it rises half of this amount. Since the height is inversely as the diameters of the openings, in circular tubes 0.01 mm. in diameter, the height in tubes would be 3.32 m. and in sheet openings 1.66 m.

In circular tubes 0.001 mm. in diameter the height in tubes would be 33.2 m., and in sheet openings 16.6 m.; and in circular tubes 0.0002 mm. in diameter—that is, openings of a size intermediate between subcapillary and capillary—the water would rise to a height of 166 m, and in sheet openings 83 m. Since many rocks have openings as small as or even smaller than this, capillary attraction may be very important in the position of the ground-water level. (See pp. 411–412.) If the openings are inclined the lengths of the openings thus filled are correspondingly great.

The height to which the water rises is independent of the character of the walls, provided the walls are wetted,[b] and hence the above numbers are applicable to rocks. However, the height to which the water rises diminishes as the temperature increases; hence, the above numbers should be modified somewhat as the top of the sea of ground water has a temperature below or above a temperature of 20° C. Ordinarily this modification is of minor importance.

Above the level to which the water may be raised as a continuous sheet in the capillary openings, the water may still creep along the walls of the openings without filling them. The obstinacy with which a film of water holds to the rock surface has already been explained. This water is that of imbibition (p. 124). In proportion as the water of imbibition varies in amount the water under molecular attraction creeps from areas of greater humidity to areas of less humidity. To the rise of the free surface due to capillarity there is a definite limit; there is no limit to the creep of water along the walls. It is presumable, however, that such movement is rela-

[a] Barker, cit., pp. 209–210.

[b] Barker, cit., p. 210.

tively slow, and that the amount of water which is thus transferred for a given surface is small. But in the soils very large surfaces are available for creep, and therefore this process is a very important one, especially in connection with plant growth. The process is one which especially pertains to the belt of weathering and is therefore later considered. (See pp. 412–423.)

The rise of the free surface of ground water above the normal level saturating the rocks, the creep of water along the walls without saturation, and the flowage of water through small tubes where there is no free surface are generally described under the term capillarity. However, it is evident that under the term thus used are included three very different things. The principles involved in the flow of water through capillary tubes are very different from those which control the free surface of ground water in capillary tubes, and these laws again are different from those which control the creep of water along the walls of openings.

Vegetation.—The roots of plants absorb ground water and transport it to the surface. The absorption of water by plant roots causes a relative deficiency of water. This deficiency is remedied by the movement of water from other places toward the roots by the forces already considered. But the influence of roots upon the flow of ground water mainly concerns the belt of weathering. The subject is therefore later considered. (See pp. 417, 422–423.)

General statements.—In conclusion, it may be said that the immediate cause of movements of ground water are five—gravity, heat, mechanical action, molecular attraction, and vegetation.

So far as the forces are concerned, the vertical component of the movements of ground water is of far the greatest importance.

But whatever the cause of the flow of ground water, the direction of movement is from places of greater pressure to places of less pressure. A current going in any direction is evidence of an excess of pressure in the rear of the current. Thus water which enters by seepage or through capillary tubes into a larger opening, such as a fissure, must be under greater pressure than the column of water into which it makes its way. Whether the motive force in the movement of the water be difference in gravitative stress or temperature, or any other cause, the excess of pressure resulting in movement is behind the current.

THE FACTOR OPPOSING WATER CIRCULATION.

The factor opposing water circulation is internal friction of the water. The internal friction is dependent upon the viscosity of the solutions. The elements entering into viscosity are the concentration of the solutions and the temperature. The more concentrated the solutions the greater the viscosity; but as the underground solutions of water are commonly not strong, this is ordinarily not an important element. The viscosity of water decreases very rapidly with increase of temperature. The relative viscosity of pure water at 0° C., 45° C., and 90° C. is respectively 100.00, 33.89, and 18.16. (See p. 141.) From these ratios it is apparent that the viscosity of water at 45° C. is about one-third of that at 0° C., and at 90° C. only about one-fifth of that at 0° C.

It is therefore clear that the higher the temperature the less the viscosity and the less the internal friction. Internal friction due to viscosity results from the variable speeds of different parts of moving water columns and from the friction between the moving and fixed portions. The greater the variations in speed of the moving parts the greater the internal friction due to this cause.

Water usually wets the surface of the rocks. In other words, there is molecular attraction between the water solutions and the minerals composing the rocks. This attraction is so strong that a thin film of water is firmly held by the walls of the openings—so firmly that it may be considered as fixed; at least the only interchange which occurs between it and the passing water currents is that of diffusion, not that of flow. Daniell says the friction between the layer of adherent water and the rock is infinite as compared with the friction within the liquid.[a] That the friction is between the moving liquid and the fixed film of liquid is shown by the fact that for any liquid the composition of the walls has no effect upon the flowage.[b] This being the case, it is clear that in the flowage of water through tubes there is no friction of the water against the rock walls. The adherent films of water are the walls of the moving columns, and the internal friction between the water and the walls is that between the fixed films and moving water.

[a] Daniell, Alfred, A text-book of the principles of physics, 3d ed., Macmillan Co., New York, 1895, p. 306.

[b] Daniell, cit., p. 316.

The greater the speed of the moving water the greater the internal friction, because of the differential movements both in the moving water and between the moving water and the films fixed to the walls. Where the rate of movement is sufficiently slow the internal friction due to viscosity drops to an almost inappreciable factor. Therefore where the movement is very slow, even if the passages be long and small, the pressure due to head may diminish very slowly. Indeed, nearly the full pressure may be maintained for long distances—many or even hundreds of kilometers. This principle is of the utmost importance in the flowage of ground water, and its applications are later developed. (See pp. 585–588.)

GENERAL STATEMENTS.

In general it may be said that in proportion as the driving forces, gravity, mechanical action, etc., are great, circulation is likely to be rapid. In proportion as the opposing force, internal friction, is great, circulation is likely to be slow. In proportion as the openings approach the circular form, circulation is likely to be rapid. In proportion as the openings are continuous, the circulation is likely to be rapid. In proportion as the pore space is great, circulation is likely to be rapid.

However, of all these various factors dependent upon the character of the openings, that of size is probably the most important; for rocks which do or do not readily transmit water may have the same proportion of pore space. For instance, if the grains be supposed to be spherical, of the same size, and arranged in the most compact fashion possible, the unoccupied space is 0.26 of the entire space, without reference to the size of the grains. Thus the relative proportion of the openings in a great bowlder conglomerate and a fine-grained clay may be the same. But the capacity for the transmission of water by the former will be indefinitely greater than by the latter. As illustrating this, an experiment showed that a quartz sand, the water of saturation of which was the same as that of a certain chalk, transmitted water under a certain pressure six hundred times as fast as the chalk.[a] In the compact soils, the particles of which are exceedingly small (see pp. 138–146), the openings between the particles are of capillary or sub-

[a] Prestwich, Joseph, Geology, chemical, physical, and stratigraphical, Clarendon Press, Oxford, vol. 1, 1886, p. 159.

capillary size. In the case of the fine soils and clays the pores may be almost wholly subcapillary, or the water is that of imbibition. In this fact we have the explanation of the retention of soil moisture in fine clays. The moisture is glued to the grains. There is practically no circulation, and the water is removed only by high temperature or high pressure, or the two combined. It follows from the foregoing that, under given conditions with a given pore space, the coarse conglomerates furnish a much larger flow than fine conglomerates, the fine conglomerates a larger flow than the sandstones, and these a vastly greater flow than the soils, clays, and shales.

Bedding, fault, joint, and fissility openings may be so close together that the pore space is very large. Ordinarily fault openings are wider spaced but larger than the joint openings, and joint openings are wider spaced and larger than the openings of fissility. It can not be said which kind of opening gives, on the average, the larger pore space. Since, however, large openings are favorable to rapid flow, for a given pore space the fault openings are likely to give a greater flow than joint openings, and joint openings a greater flow than those of fissility. This follows from the greater size of the fewer openings. To this is to be added the element of greater continuity of the larger openings, as explained on pages 130–131. Therefore, with a given pore space the flow may be vastly greater in the case of faults than in the case of joints, and much greater in the case of joints than in the case of fissility.

In this connection it may be said that the capacity of a rock for imbibition gives a very good idea as to its power of transmission. The water of imbibition, it may be recalled (see p. 124), is the amount which adheres to the walls of the openings. It is evident that in rocks containing the same percentage of water when saturated the power of transmission varies inversely as their capacity for imbibition. If the openings of a rock be very small, but numerous, there is in a cubic centimeter a large surface to which the water can adhere. If the openings be subcapillary, the water of imbibition and saturation are the same and the powers of transmission practically nil. If the spaces be capillary, the water of imbibition is much less and the power of transmission greatly increased. If the spaces be supercapillary, the water of imbibition is slight in amount and the power of transmission very great.

As already noted, there are two zones of metamorphism, that of katamorphism and that of anamorphism, and the former consists of a belt of weathering and a belt of cementation.

The major part of the water entering the ground must finally reach the surface. A small part may be combined with the rocks in the underground course of the water. A small part may possibly penetrate deep within the zone of anamorphism, but it is safe to say that at least 99 per cent of the water entering the ground reappears at the surface in some manner. A very large part of the water penetrating the soil is drawn to the surface after having taken a longer or shorter journey in the belt of weathering. A lesser part of the water joins the sea of ground water and takes a journey of greater or less distance in the belt of cementation before it reaches the surface. This journey may be merely from the top of a small hill to its base, or it may be hundreds of kilometers. An exceedingly small fraction of the water doubtless penetrates the zone of anamorphism, although, as explained (pp. 665–668), the general movement is from rather than to this zone. The underground journeys of water, whether the exceedingly short ones within the belt of weathering or the longer journeys in the belt of cementation or the zone of anamorphism, may be resolved into two components, one parallel to the surface of the earth and one at right angles to this surface. The first may be called the horizontal component, the second the vertical component. On the average, the horizontal component of the journey is many times longer than the vertical component.

GEOLOGICAL WORK OF GROUND WATER.

From the foregoing it follows that the geological work of ground water is favored by smallness of openings, by length of time, by pressure, and by high temperature. Water enters the rocks mainly through the smaller openings. A very large surface of the rock material is exposed to water action. In so far as the water passes from the smaller openings to the larger openings its geological work is lessened. The geological work may be considered as directly proportional to the time. The smaller the openings the greater the resistance, and therefore the greater the time for a given journey. That the resistance runs up very rapidly as the openings become small, and especially as they become capillary or subcapillary, has

already been shown. Since the horizontal journey is, on the average, long as compared with the vertical journey, the element of time is of much greater importance in the horizontal component of the journey than in the vertical component. The capacity for geological work is increased by pressure and by temperature. These forces, under ordinary conditions, are a function of depth, and these factors in the work mainly concern the vertical component of movement. During the downward journey the pressure and temperature steadily increase, and the amount of material in solution increases. During the upward journey the pressure and temperature diminish and the tendency for material to pass from solution or to be precipitated increases, and the amount held in solution diminishes.

Pressure and temperature are ever working together according to definite laws. Both increase in efficiency with depth, and they greatly promote the activity of deep ground waters. However, of all the varying factors, varying temperature is the one which is of incomparably the greatest importance. High temperature ordinarily results from depth of penetration; but it has been pointed out that it may result from various other causes, of which chemical action, mechanical action, and the presence of intrusive igneous rocks are the more important. The capacity which water has for taking and holding in solution various relatively insoluble compounds, and the velocity of chemical reactions, increase enormously with increase of temperature. Not only is high temperature favorable to geological work, because of the chemical activity of the water, but, as already pointed out, high temperature greatly decreases its viscosity, and this, as already explained, is favorable to depth of penetration and flow through minute openings. Since the temperature changes of ground water are commonly dependent upon depth, the vertical component of the movement of underground water is ordinarily far more important than the longer horizontal component.

The underground journey of water may occupy hundreds of years. (See pp. 585–586.) The surface of contact in very small openings is very great. Under these conditions of slow movement and small openings there is sufficient time nearly to establish complete equilibrium between the solutions and the solids with which they are in contact; but it has been seen (pp. 34–35) that rarely or never is the adjustment of a rock to its

environment complete. In so far as the adjustment is not complete, changes are going on, and the conditions are everywhere those of chemical dynamics, although the chemical action may be so slow that if the operations were conducted in a laboratory it might be concluded that the conditions were those of chemical statics. This, however, but illustrates the importance of time in geological operations.

Thus far the treatment of the circulation and work of ground water has been general. There are many other factors concerned in the circulation which have not yet been considered, but these are factors special to the different belts and zones. They will therefore be treated in Chapters VI, VII, and VIII, on the belt of weathering, the belt of cementation, and the zone of anamorphism, respectively.

CHAPTER IV.

THE ZONES AND BELTS OF METAMORPHISM.

GENERAL CONSIDERATIONS.

The various geological factors which bear upon metamorphism have been briefly discussed in the introductory chapter. It is there held that the geological factor of dominating importance is depth. Upon the basis of depth it is stated that the known crust of the earth is divisible into upper and lower zones of metamorphism; the first is called the zone of katamorphism, and the second the zone of anamorphism. It is further stated that the zone of katamorphism is divisible into two belts, an upper belt of weathering and a lower belt of cementation.

While in the introductory chapter these general statements were made, there was no attempt to show that they are correct. It is one of the purposes of this and the following chapters to furnish evidence of the utility of this classification, and to show that very different metamorphic effects follow from the work of the same forces and agents in the different belts and zones. In the present chapter a brief general statement will be made as to the characteristic reactions of the different zones and belts. This statement is primarily from physical and chemical points of view. The next chapter will treat of the alterations of minerals with reference to the different zones and belts. In succeeding chapters the alterations of the rocks in the belt of weathering, the belt of cementation, and the zone of anamorphism will be taken up in detail. The treatment will be primarily from the geological point of view, but with reference to physical and chemical principles. Finally, the alterations of the individual rocks will be considered. This and the following chapters might be regarded as a consideration of the metamorphism of the crust of the earth from the point of view of the physical-chemical principles developed in Chapters II and III.

It has just been stated that the nature of the metamorphism varies greatly with depth. The physical reasons for this are that, as depth increases, temperature and pressure increase. It has been seen in Chapters II and III that where the pressure is moderate chemical reactions are likely to be such that heat is liberated, and this is a fact whether the reactions decrease or increase the volume. It has also been seen that where the pressure is great this is likely to be the controlling factor, and that under such circumstances reactions take place which lessen the volume of the materials. Whether the reactions take place with liberation of heat or with absorption of heat is a subordinate matter; but very commonly the reactions are of a kind that absorb heat.

When the law of chemical affinity controls, and the reactions take place with liberation of heat irrespective of the volume change, the reactions may be said to be chemical-physical reactions. Where pressure is a dominant factor and reactions take place with diminution of volume irrespective of the heat change, the reactions may be said to be physical-chemical. It is because variations in the geological factor of depth result in these contrasting reactions that the lithosphere is divisible into a zone of katamorphism and a zone of anamorphism.

ZONE OF KATAMORPHISM.

From the surface of the earth to a very considerable depth below the surface (for strong rocks possibly 10,000 or 12,000 meters under quiescent geological conditions) the rocks as originally formed may contain many openings, as, for instance, those of sandstones, vesicular lavas, etc. Even if not originally porous deformation may fracture the rocks and thus produce many openings. Where the rocks contain openings chemical reactions may take place, increasing the volume of the material without rupturing the rocks and without raising them to a higher position. In the outer lithosphere the pressures and temperatures are moderate. Under such circumstances the reactions which take place are controlled mainly by the laws of chemical affinity, not by the influence of pressure. At low temperatures the fundamental chemical law is that, on the whole, the preponderating chemical reactions are those which take place with the liberation of heat in accordance with the first part of van't Hoff's law. Therefore in this zone the occurrence of a reaction in the alteration of a rock is favorable to further

alteration; for the heat developed by the first reaction is retained by the adjacent material, at least for a time, and this promotes further reaction, etc. But this tendency, as has been seen, may be reversed if the temperature becomes too high. (See p. 79.)

Since the law of chemical reactions with the liberation of heat is the dominant factor in this upper zone, alterations may take place which work with or against pressure. In the first case both the chemical reaction and the compression in volume result in the liberation of heat. In the second case the heat liberated is that developed by the chemical reaction minus that absorbed as a result of the work done in expanding the volume.

As a matter of fact, near the surface of the earth the very important reactions from the point of view of the nonmetallic elements, aside from solution, are those of oxidation, hydration, and carbonation. Oxidation and hydration commonly involve the addition of material, although the former frequently occurs by substitution of oxygen for sulphur, and therefore by desulphidation. Carbonation frequently involves the addition of material, but more commonly occurs by the substitution of CO_2 for SiO_2 and the decomposition of silicates. Often the freed silica, or a part of it, remains in situ. All of these reactions are well known to liberate heat. Commonly they decrease rather than increase the specific gravity of the minerals. Since they usually involve addition of material, it is clear that where all the residual material, or a large part of it, remains in situ the volume of the rocks is considerably increased. However, it will be seen that solution is also a very important reaction in parts of the zone of katamorphism, and where this takes place to a sufficiently great extent the volume of material may be decreased.

The main part of the oxygen and much of the carbon dioxide for oxidation and carbonation is directly or indirectly derived from the atmosphere. The water is chiefly that of the ground circulation. It is therefore clear that in the upper zone oxygen and carbon dioxide are being steadily abstracted from the atmosphere and fixed in the rocks, and ground water is steadily becoming fixed by hydration. The amount of oxygen and carbon dioxide thus fixed is great. If it were not for replenishment, it is little short of certain that the carbon dioxide of the atmosphere would have long since become exhausted. But probably the amount of water fixed by hydration is even greater than that of the gases, oxygen

and carbon dioxide. Analyses of rocks in the upper zone of metamorphism show that the amount of combined water runs as high as 4.42 per cent in shales (see p. 744), and it probably averages as high as 1.64[a] per cent. When it is remembered that the zone of katamorphism extends to a depth of thousands of meters, it is apparent that the amount of water which is thus fixed in the rocks by the process of hydration is enormous. However, it will be seen that the process of hydration, like that of carbonation, is reversed in the zone of anamorphism.

By the statement that oxidation, carbonation, and hydration are the very important characteristic reactions of the zone of katamorphism it is not meant to imply that the reverse reactions do not take place to some extent. In fact, deoxidation, decarbonation, and dehydration all occur; but oxidation, carbonation, and hydration are greatly preponderant, and indeed dominant over the reverse reactions.

Summarizing so far as the energy factors are concerned, the changes in volume commonly absorb heat, the chemical reactions dominantly liberate heat and only exceptionally absorb heat. The heat liberated by the chemical reactions is certainly very much greater than the sum of that absorbed by the volume changes and that absorbed by the exceptional chemical reactions. Therefore, so far as the rocks of the zone of katamorphism are concerned, the total of the volume and chemical changes results in the liberation of heat and the dissipation of energy.

The minerals formed in the zone of katamorphism are comparatively few in number, with low specific gravities and probably for the most part comparatively simple molecules; hence the propriety of calling this zone the zone of katamorphism, or katamorphic zone. This use of the term katamorphism is parallel to the use of the term katabolism in biology to designate those chemical changes within a living body which result in the production of simple compounds from more complex ones. The zone of katamorphism may therefore be defined as the zone in which alterations of rocks result in the production of simple compounds from more complex ones.

The zone of katamorphism is divisible into two belts, (1) an upper belt of weathering, and (2) a lower belt of cementation. The belts are

[a] This is the average taken from analyses of shales, sandstones, limestones, and volcanic and crystalline rocks, given by F. W. Clarke in Bulls. U. S. Geol. Survey No. 78, pp. 36–37, and No. 168, pp. 16–17.

delimited by the level of ground water. The separation of the belt of weathering from the belt of cementation is therefore based upon the position of an agent of metamorphism. It has been seen that the zone of katamorphism is separated from the zone of anamorphism by a reversal of the physical-chemical factors. As one would suppose, the latter distinction is of much more fundamental importance than the former.

BELT OF WEATHERING.

By some it has been proposed to call the belt of weathering that of demorphism; and to call the alterations of all rocks below this belt metamorphism. The fact that the alterations in the belt of weathering are very different from the belts below has been well known for many years. But it has not been generally recognized that the belts of weathering and cementation are delimited by the level of ground water. This is doubtless due to the fluctuations of that level and to a considerable transition band between the two belts (see pp. 423–429, 560–561); but in many places the change in the character of the alterations in passing from the belt of weathering to the belt of cementation is very sudden, and at such places is very clearly connected with the level of ground water.

The belt of weathering is therefore defined to extend from the surface to the level of ground water. In this belt all of the very important reactions characteristic of the zone of katamorphism—viz, oxidation, carbonation, hydration, and solution—are at their maximum activity; but on the whole, of these three reactions the most characteristic, but not the dominant one, is that of the carbonation of the silicates. This reaction takes place on a vast scale, producing carbonates from the silicates, and at the same time setting free silica or colloidal silicic acid. Hydration is the most extensive simple reaction in the belt of weathering. Oxidation is also very important. As will be seen, this reaction is very general in this belt, because not being saturated with water the oxygen of the atmosphere very rapidly makes its way through the porous rocks and continually supplies oxygen to replace that element used in the process of oxidation. The total effect of these chemical reactions is decomposition. While hydration and oxidation are usual for this belt, under special conditions these reactions may be reversed. In places of luxuriant vegetation and very high humidity deoxidation may take place. In regions of great heat and temporary or

permanent aridity dehydration may locally occur. As already noted, as a result of oxidation, carbonation, and hydration, the volume of the rocks would be greatly increased if all the compounds formed remained in situ; but the complex process of solution is dominant. Many of the compounds formed are dissolved in large quantities and transferred by the overground water circulation to the sea, or by the underground water circulation to the belt of cementation below. Consequently the volume of the rocks continuously decreases in the belt of weathering; and finally the resultant material may occupy but a small fraction of the original volume.

In the belt of weathering, in addition to the characteristic chemical reactions, mechanical disintegration is the rule. Thus the complex results of weathering may be classified into disintegration, decomposition, and solution. As a final result of the various mechanical and chemical changes, rocks soften and degenerate. As coherent solids they are destroyed. The processes of the belt of weathering are therefore destructive. The minerals which remain are usually few and simple, and ordinarily are not well crystallized. In the destructive processes all of the agents of metamorphism, both inorganic and organic, are actively at work. The details of these processes are fully developed in Chapter VI, on "The belt of weathering."

BELT OF CEMENTATION.

The belt of cementation extends from the bottom of the belt of weathering to the bottom of the zone of katamorphism. On the average this belt is therefore much thicker than the belt of weathering. All of the very important reactions characteristic of the zone to which the belt belongs—viz, oxidation, carbonation, and hydration—take place. Water is everywhere abundantly present in the belt, and hence hydration is the most important of the three reactions. The minerals produced by metasomatic change from the original minerals and those deposited from the solutions are likely to be strongly hydrated. The processes of carbonation and oxidation in the belt of cementation are largely limited by the amount of carbon dioxide and oxygen there contained.

It will be seen (pp. 608–610) that carbon dioxide is derived from several sources and that carbonation is usual throughout the belt, but that the oxygen is limited to that derived from above, and consequently that oxidation

is usual in only a very limited part of the belt. Not only are the processes of carbonation and oxidation subordinate to hydration, but the process of oxidation not infrequently is stopped or reversed in all but the upper part of the belt of cementation. This anomaly is due to the fact that many of the rocks contain organic materials or sulphides or both which have a strong affinity for oxygen. When the oxygen is exhausted from the water derived from the belt of weathering the reducing compounds may act directly as reducing agents or may produce reducing solutions. The demands of these reducing agents for oxygen may abstract this material from highly oxidized compounds, such as ferric oxide, basic ferric sulphate, etc. Deoxidation in the belt of cementation is most commonly the result of the burial of the higher oxide of iron and sulphates with a considerable amount of organic material in the presence of abundant water. Under these circumstances the ferric compounds may be reduced to ferrous compounds and the sulphates to sulphides.

But it is to be noted that the reduction of these compounds involves simultaneous oxidation of the organic compounds, the resultant products being CO_2 and water. The carbon dioxide may escape from the belt or enter into other combinations. For instance, as explained fully in another place, the ferrous compounds largely unite with the carbon dioxide, producing carbonates. Similar reactions may take place with reference to other less abundant metals, as, for instance, manganese, and some metals may even be reduced to the metallic condition, for instance, copper, silver, and gold. These reducing reactions in the belt of cementation, except in the case of iron, are of small consequence from a geological point of view, but they have a most important bearing upon the deposition of ores. (See Chapter XII.) It thus appears that oxidation and deoxidation are both rather important in the belt of cementation.

The changes in the belt of cementation ordinarily produce crystalline minerals. Minerals which were partly altered by processes in the belt of weathering may be regenerated. This applies only to those minerals which are adapted to the belt of cementation. The average specific gravity of the rocks is usually lessened.

It has been noted that the most characteristic reaction of the belt of weathering is solution. In contrast with this the most characteristic reaction of the belt of cementation is deposition in the openings of the

rocks. The material deposited is derived from the belt of weathering or from the alterations within the belt of cementation itself. Much of the material dissolved in the belt of weathering is continuously transferred to the belt of cementation by the downward movement of water. The total amount of material which is thus derived from the belt of weathering is not limited to the thin belt which exists at any given time; for, as a result of denudation, the belt of weathering is constantly migrating downward and encroaching upon the upper part of the belt of cementation; and thus there is never a lack of material for solution in the belt of weathering which may be dissolved and transferred to the belt of cementation. Within the belt of cementation itself the reactions of oxidation, carbonation, and hydration all increase the volume, provided all the compounds formed, or a large part of them, remain as solids. The material added to the belt of cementation from the belt of weathering, and the reactions within the belt of cementation, furnish an abundant supply of material for deposition in the openings of the rocks, whether these openings be those originally present or produced by orogenic forces. And, as a matter of fact, in the belt of cementation the openings are continuously filled by mineral matter and finally closed; but this does not show that solution may not preponderate over deposition in this belt if the effect upon the original rocks and the openings both be considered. (See pp. 612–617.) The mechanical result of the various processes is to indurate the rocks. The processes of the belt of cementation are constructive. The belt of cementation, from a geological point of view, is fully considered in Chapter VII.

BELTS OF WEATHERING AND CEMENTATION CONTRASTED.

The alterations in the belts of weathering and cementation, while not so fundamentally different as those in the zones of katamorphism and anamorphism, contrast strongly. In the belt of weathering, of the great reactions characteristic of the zone of katamorphism—oxidation, carbonation, and hydration—all are important, but carbonation is most characteristic. In the belt of cementation, of these reactions hydration is most important. In the belt of weathering, solution greatly dominates over deposition. In the belt of cementation solution and deposition are more nearly balanced, but because of reactions which increase the volume of the rocks the openings are

filled. In the belt of weathering, the material continuously decreases in volume due to solution; in the belt of cementation it continually increases in volume due to deposition of material through reactions involving expansion of volume. These changes of volume due to addition or subtraction of material commonly involve decrease in specific gravity. In the belt of weathering the mechanical results are disintegration and softening; in the belt of cementation, cementation and induration. The belt of weathering is therefore especially characterized by solution, decrease of volume, and softening, resulting in physical degeneration. The belt of cementation is especially characterized by deposition, increase of volume, and induration, resulting in physical coherence.

ZONE OF ANAMORPHISM.

At a variable depth below the surface of the earth the pressure is so great that it can not be supposed that considerable openings permanently exist. The depth at which this condition of affairs is reached depends largely upon the character of the rocks. For the strong rocks, as already noted (p. 160), this depth, under quiescent geological conditions, may be as great as 10,000 or 12,000 meters. If openings be originally present in the rocks of the zone of anamorphism, as, for instance, sandstones, vesicular lavas, etc., or be due to fracture while the rocks are not deeply buried, when such rocks become sufficiently deeply buried to be in the zone of anamorphism, it is certain that rock flowage will take place and the openings will be closed, except possibly those of subcapillary size and other minute openings in which water, carbon dioxide, or other liquids and gases are occluded. In the zone of anamorphism there is great pressure in all directions, and mechanical energy becomes the dominant factor which controls the reactions. Changes consequently take place which diminish the volume of the rocks. This volume change increases the specific gravity, and contrasts with the volume changes of the zone of katamorphism. The fundamental chemical law of energy in reference to heat is subordinate. Reactions take place with the liberation or absorption of heat, depending upon what is demanded by the pressure. Commonly, the preponderant chemical reactions are those which take place with absorption of heat. The depth at which pressure becomes dominant is variable, depending

upon the character of the rock and upon whether the conditions are mass-static or mass-mechanical.

It has been seen that at the moderate temperatures of the zone of katamorphism the preponderant chemical reactions are those which take place with the liberation of heat. As the depth below the surface increases, the temperature ever becomes higher; and consequently the temperature may become so high that the tendency for chemical reactions to take place with the liberation of heat is less dominant, and at sufficiently great depths the heat may be so great that this tendency ceases, or is even reversed. Or, using the words of van't Hoff, at high temperatures the preponderating chemical reactions, or associations, which take place at lower temperatures with the development of heat are replaced by preponderating chemical reactions, or dissociations, which take place with the absorption of heat.[a] However, at moderate depths in the zone of anamorphism under ordinary conditions the temperatures are not very high. For instance, at a depth of 9,000 meters the temperature is probably in the neighborhood of 300° C. Therefore, so far as the temperature is concerned, for that part of the crust of the earth within observation the preponderant chemical reactions would probably take place under the first part of van't Hoff's law, rather than under the second part, if it were not for the pressure. But the pressure is the dominant factor which controls the reactions. The rocks in this zone are under so great pressure in all directions that this fact demands chemical reactions which produce diminished volumes irrespective of whether heat is liberated or absorbed by them.

The very important reactions in the zone of anamorphism are silication, or union of silicic acids with bases producing silicates, and dehydration. Deoxidation is subordinate. The process of silication commonly takes place upon carbonates, and consequently involves decarbonation and the liberation of the carbon dioxide, which may escape and thus the volume be decreased. To what extent the pressure is the controlling factor in the production of this reaction is difficult to say. Probably it is the dominant cause, but it is possible that at the temperatures which prevail in this zone silicic acid may be relatively more active than at the lower temperatures of the zone of katamorphism, where carbonic is the stronger acid.

[a] Nernst, W., Theoretical chemistry, translated by C. S. Palmer, Macmillan & Co., London, 1895, p. 583.

As illustrations of the process of silication may be mentioned the formation of wollastonite from pure limestone, of tremolite from dolomitic limestone, of actinolite from ankerite, and of grünerite from siderite. (See pp. 239, 241, 243, 244.) In the impure limestones under deep-seated conditions, where numerous bases are present, various complicated silicates form, such as other pyroxenes and amphiboles, tourmaline, chondrodite, etc.

The process of dehydration involves the liberation of water. This reaction, it is safe to say, is one which is controlled by pressure. The combined water is actually squeezed out of the hydrated mineral particles, transforming them to less hydrous and to anhydrous forms in a manner similar to that in which free water is pressed from a sponge.

Whether or not pressure in the zone of anamorphism is sufficient to deoxidize compounds is uncertain. Certainly it can not be asserted that the pressure is sufficient to squeeze out a part of the oxygen of hematite, thus transforming it to magnetite. So far as deoxidation occurs, probably the oxygen abstracted from the rocks usually unites with the elements of organic compounds, thus producing carbon dioxide and water. Thus the chief products liberated by silication, dehydration, and deoxidation are carbon dioxide and water. These join the interstitial water in the subcapillary spaces and probably slowly escape into the zone of katamorphism above. (See pp. 665–667.) This results in loss of material, and since the specific gravity of the minerals is increased on the average, the volume of the rocks is decreased.

Besides the above processes, condensation may also be accomplished by recrystallization, although this process generally takes place in connection with them. The process of recrystallization produces a rearrangement of the elements in such a way as to form compounds of higher specific gravity. This is well illustrated by the devitrification of glass.

The minerals produced in the zone of anamorphism are numerous, definite, stable, crystalline, of high specific gravities, and probably have complex molecules. The rocks formed are compact and strong. The lower zone may therefore properly be called the zone of anamorphism, or anamorphic zone. This use of the term anamorphism is parallel to the use of the term anabolism in biology to designate those chemical changes in a living body which result in the production of complex compounds from more

simple ones. The zone of anamorphism may be defined as the zone in which alterations of rocks result in the production of complex compounds from more simple ones.

Summarizing the energy factors in the zone of anamorphism, so far as the volume change is concerned, the result is to liberate heat; so far as the chemical reactions are concerned, heat may be liberated or absorbed, but the latter reaction is more common. In the latter case the heat absorbed is almost certainly much greater than that liberated by decrease of volume. If it were not that a considerable number of the chemical reactions liberate heat, it would be certain that heat is absorbed in the zone of anamorphism But the heat liberated by some chemical reactions must be added to that liberated by decrease of volume. Whether this sum is as great as the heat absorbed by the preponderating chemical reactions is somewhat uncertain; but it is thought to be rather probable, for the compounds immediately concerned in the reactions, that the total effect is to absorb heat and store energy. However, in order to accomplish this, energy must be derived from an outside source, and when all the factors which in any way affect the reactions are taken into account, including the movement of the superincumbent material, heat is dissipated and energy lost. (See p. 182.)

RELATIONS OF ZONES OF KATAMORPHISM AND ANAMORPHISM.

We shall now consider the zones of metamorphism together with reference to the energy factors. So far as the chemical reactions are concerned, it has been seen that they may take place with liberation or absorption of heat. So far as heat is liberated energy is dissipated. So far as heat is absorbed energy is stored. The change in volume may also result in the dissipation or storage of energy. Where increase of volume is preponderant energy may be stored (1) by increasing the volume of the rocks affected by the reaction or (2) by elevating the overlying rocks in order that the space shall be available for the expenditure. In a given case the energy may be stored by (1) or (2) or a combination of them. Where decrease of volume is preponderant energy is dissipated (1) by the decrease of volume of the rock affected by the reaction or (2) by subsidence of the overlying material, or by both. Below the extreme outer film of the earth the factor of elevation or subsidence of the overlying rocks is of vastly greater importance than the volume change, and the relative

importance of this factor steadily increases with depth. This is more broadly true in the case of increase of volume than in that of decrease of volume; for in the latter case in the zone of katamorphism the strength of the rocks near the surface may prevent subsidence, and the decrease of volume simply produce porosity. A common illustration of that is vesicular dolomite. However, in the zone of anamorphism, when the reactions result in decrease of volume, subsidence occurs and energy is dissipated. The importance of the necessity of lifting the overlying material in order to find more room in the case of increase of volume is well illustrated by the frequent rapid hydration or slacking, with great expansion and rapid disintegration, which follows when a partly hydrated rock, buried but a few feet, is brought to the surface.[a] Apparently when buried the tendency for hydration and necessary expansion with liberation of heat was not sufficient to lift the superjacent material. When the necessity of elevating the superjacent material was removed by transfer to the surface the process of hydration and expansion went on to completion with great rapidity.

I conclude from the foregoing that in so far as energy is concerned there are four cases. Chemical reaction may (1) release energy and result in the liberation of heat, or (2) may consume energy and result in the absorption of heat. The change of volume may be (3) by decrease of volume, and result in the release of energy and the liberation of heat, or (4) by increase of volume, and result in the consumption of energy and in the absorption of heat. (1) and (3) will be called plus, and when they are combined the heat developed is equal to their sum; (2) and (4) will be called minus, and when they are combined the heat absorbed is equal to their sum. When (1) and (4) or (2) and (3) are combined heat may be liberated or absorbed, and consequently energy dissipated or stored, depending upon the relative values of the opposing factors.

It has been noted that the three important reactions in the zone of katamorphism are oxidation, carbonation, and hydration; and in the zone of anamorphism are deoxidation, silication, and dehydration.

Since all of the abundant metallic elements except iron are completely oxidized as they occur in the original rocks, the important inorganic compounds which are oxidized in the zone of katamorphism are mainly those

[a] Merrill, G. P., Disintegration of the granitic rocks of the District of Columbia: Bull. Geol. Soc. America, vol. 6, 1895, p. 332.

of iron. Iron occurs extensively in the ferrous form, in magnetite, in carbonates, and in silicates. To a considerable extent it occurs as a sulphide. To a small extent it occurs as metallic iron. In all of these forms it is capable of oxidation. The main result of the oxidation of these compounds, so far as the iron is concerned, is to change the monoxide to ferric oxide. But where it is present as a sulphide it may be changed to a sulphate, and then be thrown down as a basic ferric sulphate. Ferric oxide, hydrous or anhydrous, is an important constituent in the sedimentary rocks, and its presence is, without doubt, largely due to oxidation in the zone of katamorphism. To a far less extent other metals, such as copper, lead, zinc, etc., occur in the native form, in partially oxidized forms, or as sulphides. All these substances may be oxidized. These substances have little importance in general geology, but are of great importance in the production of ores. All of the reactions of oxidation take place with great liberation of heat and with increase of volume. In the zone of anamorphism partial or complete deoxidation of the highly oxidized compounds may occur. The ferric iron may be reduced to the ferrous form. The sulphates of iron and the other metals may be reduced to sulphides. In most cases the reducing agent is organic matter. The reduction of the metals by organic compounds results in the oxidation of the carbon and hydrogen, thus producing carbon dioxide and water. The carbon dioxide and water largely escape. Where reducing agents are not present the highly oxidized materials produced in the zone of katamorphism commonly remain in this condition even if the material passes into the zone of anamorphism. Deoxidation can not, therefore, be said to be characteristic of the zone of anamorphism to the degree that oxidation is characteristic of the zone of katamorphism. The reducing reactions all take place with great absorption of heat, so far as the metals are concerned, and with decrease of volume. However, since heat is liberated by the oxidation of the carbon and hydrogen, it is probable that the sum total of the heat reaction in deoxidation in the zone of anamorphism is to liberate heat.

In the matter of oxidation and deoxidation, the zone of katamorphism presents a case in which the chemical law of the liberation of heat controls, without reference to change in volume, while in the zone of anamorphism the pressure tending to produce decrease of volume and chemical reactions with the liberation of heat probably work together.

Another set of reactions, of the most fundamental importance and widespread character, which occur in an opposite sense in the two zones of metamorphism are the mutual replacements of carbon dioxide and silicon dioxide. It has already been noted that near the surface, or in the zone of katamorphism, carbonic replaces silicic acid. Deep below the surface, or in the zone of anamorphism, silicic replaces carbonic acid. Under the conditions near the surface, where the pressure is small and the temperature is low, carbonic is the stronger acid; and under the conditions deep below the surface, where the pressure is great and the temperature is high, silicic is the stronger acid. The importance of the mutual replacement of these compounds under different conditions makes it advisable to summarize the chemical analogies of silicon and carbon. Silicon is the characteristic element of inorganic compounds; carbon is the characteristic element of organic compounds. How closely analogous are these two elements is shown by the following comparative table:

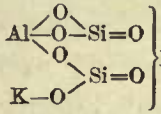
Chemical relations of silicon and carbon.

SILICON.	CARBON.
SiO_2 silica, anhydride, solid	CO_2 carbon dioxide, gas.
SiH_4 silicon hydride, gas	CH_4 methane, gas.
$SiCl_4$ silicon chloride, liquid	CCl_4 carbon tetrachloride, liquid.
Boils at 57°	Boils at 76°.
$SiHCl_3$ silicon chloroform, liquid	$CHCl_3$ chloroform, liquid.
Boils at 34°	Boils at 60°.
$Si(C_2H_5)_4$ silicon ethyl, liquid	$C(C_2H_5)_4$ tetraethylmethane, liquid.
Boils at 150°	Boils at 120°.
$Si(OC_2H_5)_4$ ethyl orthosilicate, liquid	$C(OC_2H_5)_4$ ethyl orthocarbonate, liquid.
Boils at 160°	Boils at 158°. (See Mendeléeff, Vol. II, Chap. XVIII, pp. 99–100.)
H_4SiO_4 orthosilicic acid	H_4CO_4 orthocarbonic acid.
$SiO_4(C_2H_5)_4$ ethyl orthosilicate.	
$(MgFe)_2SiO_4$ olivine $CaAl_2(SiO_4)_2$ anorthite $R''_3R'''_2(SiO_4)_3$ garnet, etc. — Natural orthosilicates.	Exists only in certain artificial organic compounds, as ethyl orthocarbonate, $CO_4(C_2H_5)_4$.
H_2SiO_3 metasilicic acid	H_2CO_3 carbonic acid.
	Exists in salts and in solution. Forms normal (neutral) and acid salts ("bicarbonates").

Chemical relations of silicon and carbon—Continued.

SILICON.

$KAl(SiO_3)_2$ leucite

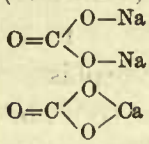


Natural metasilicates.

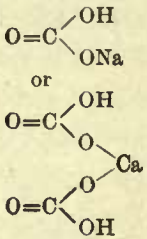
$Be_3Al_2(SiO_3)_6$ beryl, etc.

CARBON.

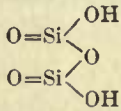
(normal salts)

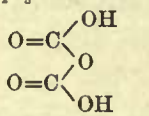


(acid salts)



$H_2Si_2O_5$ disilicic or dimetasilicic acid.....$H_2C_2O_5$ dicarbonic or pyrocarbonic acid.





Si : O :: 2 : 7 for basic salts.

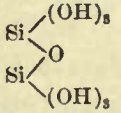
Si : O :: 2 : 5 for acid salts.

Not known in free state.

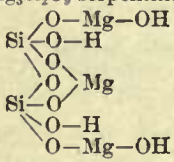
Known only in salts, as $C_2O_3(NaO)_2$, produced by heating the acid salt.

$LiAl(Si_2O_5)_2$ petalite.

$H_6Si_2O_7$ diorthosilicic acid .....The corresponding carbon acid does not exist.



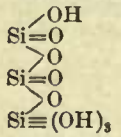
$H_4Mg_3Si_2O_9$ serpentine (normal salt).



$H_2CaSi_2O_8+H_2O$ okenite (acid salt).

$H_4Si_3O_8$ polysilicic acid or trisilicic acid.....The corresponding carbon acid does not exist.

(May be considered as metasilicic acid plus disilicic acid.)



(neutral salts of trisilicic acid)

$KAlSi_3O_8$ orthoclase.

$NaAlSi_3O_8$ albite.

Another close analogy which exists between the carbonates and the silicates is the fact that many salts of both give alkaline reactions, or under the theory of dissociation are hydrolized as explained (pp. 86–87), and that alkalinity increases with the temperature.

The specific volumes of the silicates and carbonates also have very close relations. In general the specific volumes (the molecular weights divided by the specific gravities) of the silicon compound are slightly the greater. The comparative specific volumes of a number of the correlative silicon and carbon compounds are as follows:[a]

Specific volumes of silicon and carbon compounds.

$SiCl_4$	112	CCl_4	94
$SiHCl_3$	82	$CHCl_3$	81
$Si(OC_2H_5)_4$	201	$C(OC_2H_5)_4$	186
$CaSiO_3$	41	$CaCO_3$	37

The specific volumes of SiO_2 and CO_2 are wholly different, but this is explained by the fact that one is a solid and the other a gas.

Since the specific volumes of the carbon compounds are less than those of the silicon compounds, if there be a simple substitution of carbon for silicon the volume is decreased; if silicon for carbon, the volume is increased. However, as a matter of fact, the changes in the rocks are never so simple as this. The volume changes in carbonation with desilication, and in silication with decarbonation in the rocks largely depend upon whether the reacting and resultant compounds are gaseous, liquid, or solid, and whether the products remain as solids or are dissolved and transported elsewhere.

In the zone of katamorphism carbon dioxide replaces silicon dioxide ordinarily with liberation of heat

The fact of the carbonation of the silicates is well known. So far as I know, the importance of this process was first realized by Bischof. He attributes the general decomposition of the rocks near the surface mainly to the action of carbonic acid, thus producing the carbonates which are found in spring water. He shows by experiment that "the silicates of alkalies, alkaline earths, protoxides of iron and manganese are decomposed

[a] Mendeléeff, D., The principles of chemistry, translated by Geo. Kamensky, Longmans, Green & Co., London, 1897, vol. 2, pp. 99–100.

by carbonic acid at ordinary temperatures."[a] But he says that, since carbonic acid does not combine with alumina or peroxide of iron, the silicates of these compounds are not decomposed by carbonic acid.[b] However, we now know that the process of carbonation takes place with all the natural silicates. It will be shown in Chapter VII that this process of carbonation goes on throughout the entire zone of katamorphism, but it is in the upper of the two belts of the zone of katamorphism, that of weathering, in which the process of carbonation goes on with greatest rapidity and is especially characteristic. Simultaneously with the substitution of the carbon dioxide for the silica much of the silica separates as colloidal silicic acid, is taken into solution, and is carried downward to the belt of cementation by the percolating waters. In this belt the silica is deposited on an enormous scale. The carbon dioxide is furnished in solution, being mainly derived directly or indirectly from the atmosphere. When carbon dioxide replaces silicon dioxide the volume would be decreased, provided all of the silicic acid were abstracted in solution. But it is probable that the larger portion of the silica set free in the zone of katamorphism by carbonation is deposited in the belt of cementation, and therefore the volume of the zone of katamorphism as a whole, so far as this reaction is concerned, is increased. The deposition of silica in the belt of cementation is probably accompanied by a considerable absorption of heat, under the law that the negative value of the heat of solution is greater the more insoluble the substance.

Carbonation in the zone of katamorphism may take place without replacing silica, as in the case of the union of carbon dioxide with iron oxide in magnetite, thus producing iron carbonate. In this case the liberation of heat and the increase in volume are both great.

In the zone of anamorphism, and especially under mass-mechanical conditions, silica replaces carbon dioxide in the carbonates on the most extensive scale. So far as I am aware, Bischof was the first to realize that under proper conditions the process of carbonation of the silicates could be reversed. He shows by experiment that carbonates of calcium, magnesium, and iron are decomposed by silica at a boiling temperature, and cor-

[a] Bischof, Gustav, Elements of chemical and physical geology, translated by Paul and Drummond, Harrison & Sons, London, vol. 1, 1854, p. 2.

[b] Bischof, cit., vol. 1, pp. 4–5.

rectly infers that when any of these carbonates occur with quartz at a sufficient depth within the earth, where a temperature of 100° C. is reached, this reaction may take place. He calculates that this depth will be 2,440 meters. He correctly infers that the presence of abundant carbon dioxide in deep-seated waters is probably due to this process of silication.[a] We now understand that under conditions of moderate pressure and temperature not only are the carbonates which Bischof mentioned decomposed, but other carbonates may be altered in a similar manner. However, it is noteworthy that the carbonates which Bischof mentioned are those of predominant importance.

The substitution of silicon for carbon would result in increase of volume provided silica were derived from the solutions and the carbon dioxide passed into the solutions. But in the process of silication in the belt of anamorphism little material is available from outside sources. Therefore the most of the silica which replaces carbon dioxide in carbonates must be considered as a solid. It is probable that a large part of the freed carbon dioxide slowly escapes; for at temperatures prevailing in the zone of anamorphism the carbon dioxide is above its critical temperature, and therefore a gas, and probably slowly makes its way through the subcapillary spaces to the zone of katamorphism (see p. 667.) Hence the volume comparison must be made between the carbonate and replacing silica combined and the resultant silicate. On this basis there is a marked diminution of volume. One of the simplest illustrations of the formation of the silicates with condensation of volume is the development of wollastonite from calcium carbonate and quartz. In this change the volume of the solid remainder is decreased 31.48 per cent. However, this calculated decrease is somewhat too great; for it will be seen (p. 667) that some of the carbon dioxide does not escape, but is retained in the rocks in the form of numerous inclusions.

It appears from the foregoing that in the replacement of silicon dioxide by carbon dioxide in the zone of katamorphism, the chemical law of reactions with liberation of heat dominates over that of pressure; and that in the substitution of silicon dioxide for carbon dioxide in the zone of anamorphism the physical law that pressure demands decrease of volume dominates over the chemical law of reactions with liberation of heat.

[a] Bischof, cit., vol. 1, pp. 237–241.

The third important case in which the reactions occur in the opposite sense in the zones of katamorphism and anamorphism are hydration and dehydration.

Hydration is a characteristic reaction of the zone of katamorphism, only less important than that of carbonation; moreover, hydration occurs on a great scale both in the belt of weathering and in that of cementation. That hydration occurs extensively deep in the belt of cementation is evidenced by the hydrated minerals which develop in the cavities of the rather deeply buried rocks, such as the amygdules of amygdaloids. Hydration represents, in the words of the first part of van't Hoff's law, "an association which takes place with great liberation of heat." This process also results in very considerable increase of volume, provided all or nearly all of the products formed remain in situ.

Dehydration is a characteristic reaction of the zone of anamorphism, only less important than that of silication. When the hydrated minerals formed in the belt of katamorphism pass into the zone of anamorphism by deep burial they are dehydrated. The pressure, or the high temperature, or the two combined, unite to drive off a large part of the water. Dehydration, in the words of the second part of van't Hoff's law, represents "a dissociation which takes place with great absorption of heat" and it takes place with decrease of volume.

Therefore, so far as hydration and dehydration are concerned, in the upper zone the first part of van't Hoff's law, that of chemical reactions with the liberation of heat obtains, but in the lower zone the law of diminution of volume controls, regardless of the heat effect. The first part of this statement is sufficiently evident; the second possibly needs further explanation. To drive off the combined water of rocks at ordinary pressure usually requires a temperature above 110° C. This temperature under mass-static conditions would not be found until a depth of 3,300 meters had been reached. It is certain that at depths much less than this, and at temperatures lower than this, dehydration takes place on an important scale; for it will be shown (p. 744) that in the transformation of mudstones to shales there is a loss of about one-half of the combined water. I conclude that under many circumstances the increase in temperature is not sufficient to reverse the reaction of hydration, and therefore the reversal must

be due to the pressure. However, in the lower part of the zone of anamorphism the temperature is frequently higher than 110° C., and under such circumstances both the pressure and the temperature may work together to produce dehydration.

The statement that the volume is decreased by dehydration is only true provided the separated water, or a large part of it, escapes; for the volume of the hydrated solid is less than that of the residual solid plus the separated water; therefore, if the water could not escape, pressure would tend to preserve the combination. Hence, the fact that the reaction does take place in the zone of anamorphism shows that there is sufficient pressure not only to separate the combined water from the rocks, making it free water, but to squeeze the free water from the rocks as one can squeeze the water from a sponge. The effective pressure doing the work is equal to the pressure of the adjacent rocks less the weight of an equal column of water extending to the surface. Thus, under mass-static conditions, if the rocks have a specific gravity of 2.7, the effective weight in producing dehydration and driving out the free water at a depth of 3,300 meters is that of a column of material of this height with specific gravity of 1.7. Under mass-mechanical conditions, where the pressure as a result of thrust may be much greater than that due to weight, the effective pressure tending to separate the combined water is much greater. Consequently, under such conditions dehydration may occur at much less depth than under mass-static conditions. (See pp. 766–768.)

One or two minerals may be mentioned which illustrate the processes of hydration and dehydration in the two physical-chemical zones. Near the surface and to a considerable depth, under mass-static conditions, limonite and other hydrated oxides of iron develop. Deeper down, and especially in connection with mass-mechanical action, limonite is dehydrated, and hematite is produced. As another illustration may be mentioned the somewhat similar compounds, chlorite and biotite. Near the surface and under quiescent geological conditions chlorite forms. Deep below the surface, and especially under mass-mechanical conditions, biotite ordinarily develops. This is nowhere better illustrated than in the Michigamme formation in the Marquette district of the Lake Superior region, where these two minerals directly replace each other under the law just

stated.[a] In the zone of katamorphism the complex hydrous silicates, such as the kaolins, serpentines, and zeolites form. In the zone of anamorphism these minerals are largely dehydrated, and such minerals as muscovite, andalusite, garnet, staurolite, etc., are produced.

The physical-chemical principles cited (pp. 45–123) give reasons for the existence of the above reverse sets of reactions in the two zones. We can now give chemical or physical causes why oxidation, carbonation, and hydration take place in the zone of katamorphism, and deoxidation, silication, and dehydration in the zone of anamorphism, and so on for other reactions.

While each of these sets of processes is particularly characteristic of one zone, it is not meant to imply that each reaction may not occur in both zones. But in the zone of katamorphism, oxidation, carbonation, and hydration greatly predominate over the reverse processes. On the other hand, in the zone of anamorphism, deoxidation, silication, and dehydration predominate over the reverse processes.

If all of these sets of processes reversed as preponderant reactions at the same depth, it would be possible to sharply separate the zones of katamorphism and anamorphism. If, for instance, for a given region above a depth of 10,000 meters the sum totals of the oxidation, carbonation, and hydration were greater than the sum totals of reverse processes, the zone of katamorphism would be sharply separated from the zone of anamorphism at this depth. But this is not the case. The reversal of each pair of processes occurs at different depths; and, further, the reversal for a given pair of processes is at different depths under different conditions. One of the most important of these is as to whether the conditions are mass-static or mass-mechanical.

Of the three sets of reversing reactions, oxidation and deoxidation, carbonation and silication, hydration and dehydration, the first reverses with the least depth and pressure, the second requires the greatest depth and pressure, and the last a mean depth and pressure. It has already been noted that oxidation very frequently is replaced by deoxidation in the lower part of the zone of katamorphism. It is certain that the process of hydration is very greatly stayed, if it does not altogether cease, and may

[a] Van Hise, C. R., and Bayley, W. S., The Marquette iron-bearing district of Michigan: Mon. U. S. Geol. Survey, vol. 28, 1897, pp. 444–459.

even be reversed in the lower part of the zone of katamorphism. It is therefore apparent that the two zones are not sharply delimited. In general, however, it may be said that the outer zone to a depth in which oxidation, carbonation, and hydration preponderate is that of katamorphism, and that the deeper-lying zone, in which the reverse of these processes preponderate, is that of anamorphism. But carbonation and its opposite, desilication, are the most fundamental reactions of the zone of katamorphism. Silication and decarbonation are the most fundamental reactions of the zone of anamorphism. By these reactions more than by any others, these zones are delimited. The three sets of reversing reactions, oxidation and deoxidation, carbonation and silication, hydration and dehydration, constitute three cycles in metamorphism. The second of these cycles was recognized many years ago by Bischof (see pp. 176–177), and was called the carbono-silicic cycle.

From the foregoing statement it is clear that the work of the zones of katamorphism and anamorphism are opposed to each other. What the one is doing the other is undoing. At the present time it is therefore possible that in the case of any one of the pairs of opposed reactions, considering both the zones, either one of them preponderates, or that they are approximately balanced. For instance, the amount of water being fixed in the zone of katamorphism may be greater or less than the amount of water being freed by dehydration in the zone of anamorphism, or the two may be nearly balanced. The same statement may be made in reference to the other reversing reactions. Upon the preponderance of these opposing sets of reactions in the opposite zones depends the answer to the question whether, on the whole, oxygen, carbon dioxide, and water from the atmosphere and hydrosphere are being fixed or freed by metamorphism. This question is considered in Chapter XI.

While the zones of katamorphism and anamorphism are separated from each other by contrasting reactions, all reactions do not reverse in the two physical-chemical zones. The first part of van't Hoff's law of heat and the law of pressure may work together—that is, in both zones reactions may occur which, simultaneously with the liberation of heat by chemical action, also result in liberation of heat by condensation. In so far as there are cases of this kind it is to be presumed that such reactions are common to both zones. As an instance in which heat is probably evolved

both by the chemical reactions and by the volume change in both zones may be mentioned the devitrification of glass. (See Chapter V, pp. 251–252.) The chemical reaction is presumably under the first part of van't Hoff's law, and the volume is decreased. Another instance of chemical reaction with the liberation of heat and condensation of volume is the replacement of calcium by magnesium in limestone, thus transforming the rock into dolomite.[a]

It is thought to be certain that the total of all the changes taking place in the whole of the mass of rocks concerned in any given modification of the lithosphere results in the dissipation of energy, and it is believed that such is the fact for each of the physical-chemical zones separately. In the zone of katamorphism the chemical reactions result in liberation of heat; the average volume reaction results in absorption of heat. It is, however, thought certain that the residual is in favor of the former. In the zone of anamorphism the average of the chemical reactions results in absorption of heat; the average of the volume reactions results in the liberation of heat. It has already been seen (pp. 170–171) that the amount of energy required for the volume change rapidly increases with depth, and in the lower zone it is thought that the heat liberated from the volume changes is greater than the heat absorbed by the chemical reactions, and therefore that the residual is in favor of the liberation of heat.

Hence, it is concluded that the changes which take place in each of the zones are under the general law of the running down of energy into the form of heat which is dissipated, and this accords with the apparent order of the universe.

A corollary to the foregoing pages is the conclusion that in the upper zone, where pressure is relatively unimportant, on the average, alterations result in the expansion of the volume of the rocks; and that in the deeper-seated zone, where pressure is important or dominant, on the average the alterations result in the contraction of the volume of the rocks. It follows as a further conclusion from this that the tendency of the alterations

[a] The verification from authorities of the heat of the chemical reactions and the volume relations for the majority of the changes above mentioned have been very kindly made for me by Mr. A. T. Lincoln. Mr. Lincoln either has found the results used in the works of Thomsen, Ostwald, Mendeléeff, or other standard authorities, or from the data there found has been able to calculate results which answer the specific questions I gave to him.

in the first zone is, on the average, to produce minerals of lower specific gravity than the original minerals, while in the deeper-seated zone the tendency, on the average, is to produce minerals of higher specific gravity.

Illustrations of the first rule are the minerals produced by the disintegration and decomposition of rocks near the surface, out of which the sedimentary rocks are built. Some of these are kaolinite (sp. gr. 2.6–2.63), quartz (sp. gr. 2.65), calcite (sp. gr. 2.72), chlorite (sp. gr. 2.60–2.96), serpentine (sp. gr. 2.5–2.65), talc (sp. gr. 2.7–2.8), zeolite (sp. gr. 2–2.4), limonite (sp. gr. 3.5–3.96), etc. All of these minerals and most of the other abundant undecomposed minerals, such as feldspar (sp. gr. 2.55–2.75), which make up great masses of sedimentary rocks, have comparatively low specific gravities.

The second rule is illustrated by the change from low to high specific gravity of the minerals where the sedimentary rocks are metamorphosed. As just seen, the minerals which compose the unaltered sedimentary rocks are originally those of low specific gravity. Some of the abundant resultant minerals in the equivalent metamorphosed rocks have considerably higher specific gravities, as, for instance, muscovite (sp. gr. 2.76–3), biotite (sp. gr. 2.7–3.1), pyroxene (sp. gr. 3.2–3.6), and amphibole (sp. gr. 2.9–3.4), and the still heavier minerals, garnet (sp. gr. 3.15–4.3), staurolite (sp. gr. 3.65–3.75), chloritoid (sp. gr. 3.52–3.57), hematite (sp. gr. 4.9–5.3), and magnetite (sp. gr. 5.168–5.180). Less common heavy minerals are andalusite (sp. gr. 3.16–3.2), fibrolite (sp. gr. 3.23–3.24), and chondrodite (sp. gr. 3.118–3.24). With the above are the lighter minerals, quartz and feldspar; but even these are quite as heavy as the average of the original minerals.

It is noticeable in the altered rocks that in proportion as deep-seated metamorphism is advanced the heavier of the above minerals appear. In the early stages of the metamorphism of shales, mica develops plentifully, and the rocks become slates. Where the metamorphism is more intense the heavier minerals, garnet and staurolite, appear, the material of the previously developed micas being absorbed at the places occupied by the garnet and staurolite.

The garnet-, staurolite-, chloritoid-, andalusite-, and tourmaline- bearing schists and gneisses of the Penokee and Marquette districts of Michigan and Wisconsin and the Black Hills of South Dakota, produced by the

alteration of clastic rocks, are perfect illustrations of the above changes.[a] In these rocks the acid feldspars (sp. gr. 2.55–2.67) have extensively altered into quartz (sp. gr. 2.65) and mica (sp. gr. 2.76–3.01), and therefore have passed into minerals denser on the average than those from which they were derived. Also the heavier minerals, garnet, etc., have developed on an extensive scale in the more metamorphosed varieties.

When all the minerals formed are taken into account the average is as given. But it is not supposed that there are not exceptions to each of the rules that in the upper physical-chemical zone lighter minerals form and in the lower zone heavier minerals develop. Indeed exceptions are known to both. An illustration of such exceptions in the upper zone is the case already mentioned (see pp. 181–182), the replacement of calcium by magnesium. A case of the change from higher to lower specific gravity in the lower zone is the alteration of pyroxene into amphibole. On the average the former is slightly heavier, and yet in the lower zone, under both mass-static and mass-mechanical conditions, pyroxene very generally alters to amphibole. Of course in this transformation a change simultaneously takes place in the chemical composition (and this may have an effect upon the volume of the minerals); for, in general, pyroxene contains a greater proportion of calcium and less proportions of magnesium and iron than the amphiboles. If all of the compounds concerned in the change were taken into account this apparent exception to the rule of the production of compounds of high specific gravity in the lower zone would probably disappear. In some of the deepest-seated schists, pyroxene and not amphibole has developed, and it is suspected that sufficiently deep this is the rule. If this be the case the real meaning of the change of pyroxene to amphibole is, in order that pressure shall become the dominant factor for each of the minerals as well as for the average, that the pressure must be very great.

But whatever exceptions may be discovered in the cases of individual minerals, the rules that in the upper physical-chemical zone the alterations, on the average, result in decrease of specific gravity, and that in the lower

[a] Irving, R. D., and Van Hise, C. R., The Penokee iron-bearing series of Michigan and Wisconsin: Mon. U. S. Geol. Survey, vol. 19, 1892, pp. 302–331; also vol. 28, 1895, pp. 448–450, 452–454, 456–459. Van Hise, C. R., The pre-Cambrian rocks of the Black Hills: Bull. Geol. Soc. America, vol. 1, 1890, pp. 222–229.

zone the alterations result in increase in specific gravity, are believed to hold and to be of fundamental importance in the metamorphism of rocks.[a]

This principle of the development of minerals of low specific gravity near the surface and of high specific gravity at depth has a direct application to the crystallization of magmas. From a magma of a given chemical composition there can be little doubt that the greater the depth, and therefore the greater the pressure at which crystallization occurs, the higher the average specific gravity of the rocks. In this treatise no attempt will be made to work out the applications of the rule to individual minerals and rocks, but one illustration in reference to minerals and one illustration in reference to rocks may be cited. It is well known that in the lavas silica frequently crystallizes in the form of tridymite (sp. gr. 2.28–2.33), but that in the deep-seated igneous rocks quartz (sp. gr. 2.65) only is found. It is believed that the explanation of this fact is that near the surface other factors than pressure control the crystallization, and therefore that the less heavy form of crystallized silica—tridymite—may be produced; and that in the lower zone pressure is the determinative factor in the crystallization, and therefore that the heavy form of crystallized silica—quartz—invariably results. An illustration in reference to rocks is the presence or absence of glass. Glass has a lower specific gravity than the equivalent crystallized substance. It is well known that where magmas crystallize near the surface glass is a frequent product, and that where magmas crystallize deep below the surface glass is either very subordinate or absent altogether. While other factors besides pressure enter into this result, it is believed that the frequent presence of glass near the surface and the presence of dense crystallized minerals in the equivalent deeper-seated rocks crystallizing from magmas is a very striking illustration of the truth of the principle of the development of minerals and rocks of low density where the pressure is small and of great density where the pressure is great.

[a] The above conclusions as to the condensation of material at considerable depths has an important bearing upon Reade's theory of mountain making. (Reade, T. Mellard, The origin of mountain making, London, 1886.) His explanation of the rise of mountains is that the volume of the thick deposits of sediments increases as a consequence of the rise of the isogeotherms. I believe that possible expansion due to this cause is more than compensated in the case of the sediments by the mechanical bringing of the particles closer together as the result of pressure, in many instances to the practical disappearance of the interspaces, and by the condensation of the material itself by the physical-chemical changes above explained. The condensation also has a bearing upon estimates of crustal shortening. In so far as condensation occurs, shortening of the outer crust of the earth may allow accommodation to a nucleus of decreasing size without crustal corrugation.

In conclusion of this part of the subject it may be said that in the zone of katamorphism the alterations are mainly controlled by the chemical law that reactions take place with liberation of heat, and this ordinarily results in increase of volume, provided the compounds which form remain as solids. In the zone of anamorphism the reactions are mainly controlled by the physical law that reactions take place with decrease of volume, and this commonly results in chemical reactions with absorption of heat. In the upper zone chemical law is the determinative factor in the reactions; in the lower, physical law. In the upper zone the important chemical reactions are those of oxidation, carbonation (involving desilication), and hydration; in the lower zone the important reactions are those of deoxidation, silication (involving decarbonation), and dehydration. In the upper zone the minerals are few in number, of low specific gravity, and probably of simple molecular structure; in the lower zone the minerals are numerous, of high specific gravity, and probably of complex molecular structure.

If one were to select three words which roughly represent the characteristics of the alterations in the belt of weathering, the belt of cementation, and the zone of anamorphism, these three words would be, respectively, destruction, construction, and reconstruction.

GENERAL CONSIDERATIONS.

It is now apparent that a geological classification of metamorphism dependent upon depth carries with it profound chemical and physical significance. Not only is the classification applicable to all parts of the earth, but the alterations of the zones of katamorphism and anamorphism are more fundamentally different than any distinction heretofore made with reference to metamorphism. Also, the alterations of the belt of weathering and the belt of cementation of the zone of katamorphism, again dependent upon depth, are very different so far as the geological facts are concerned, but are closely allied from the chemical and physical point of view, and therefore belong together in a single zone.

It is further to be noted that the classification is based upon one idea throughout. There is no overlapping, although the different belts and zones are side by side and grade into one another.

After the universal geological applicability of the classification proposed

is understood and its chemical and physical significance appreciated, one sees how partial, how overlapping, and how variable are the criteria upon which are based such classifications as thermo-metamorphism, hydro-metamorphism, dynamic metamorphism, contact metamorphism, regional metamorphism, etc.

RELATIONS OF ZONES OF KATAMORPHISM AND ANAMORPHISM TO ZONES OF FRACTURE AND FLOWAGE.

In connection with metamorphism in the zones of katamorphism and anamorphism it may be recalled that the outer part of the surface of the earth may be divided into two zones upon a different basis.[a] It has been shown from the structural point of view that we may divide the rocks of which we have knowledge into an upper zone of rock fracture and a lower zone of rock flowage. Where the rocks are subjected to deformation while in the upper zone they mainly undergo mass fractures called bedding partings, faults, joints, fissility, etc. The deformation is accomplished but to a slight extent by fracturing of the individual particles and by differential movement between them. In the zone of fracture openings other than those formed by deformation may exist. In the sedimentary rocks are openings between the grains. In the lavas there may be gas openings. So far as the mass-mechanical forces are concerned openings of all of these different classes may persist indefinitely. In the lower zone—that of rock flowage—if openings could be supposed to be produced in any way, the pressure is so great that the rock flows and fills them nearly completely, except that water solutions and gases are to a small extent included in minute cavities. Rock flowage will be subsequently shown to be mainly accomplished by innumerable fractures of the mineral particles, by the recrystallization of the mineral particles, or by a combination of the two processes in any proportion. Mass fractures play but a subordinate part.

UPPER LIMIT OF ZONE OF FLOWAGE.

The depth at which deformation by flowage occurs depends upon many factors, of which the character of the rocks, the temperature, the water content, and the speed of deformation are of consequence. The more

[a] Van Hise, C. R., Principles of North American pre-Cambrian geology; with an appendix on flow and fracture of rocks as related to structure, by L. M. Hoskins: Sixteenth Ann. Rept. U. S. Geol. Survey, pt. 1, 1896, p. 589.

important factors which enter into the character of the rocks are the strength and the mineral composition. The stronger the rock the greater is the depth at which flowage begins. The rocks the materials of which are refractory, as, for instance, those composed of quartz and feldspar, require a greater depth in order that deformation may take place by flowage than those rocks the materials of which are readily acted upon chemically, as, for instance, calcite.

The higher the temperature the less the depth in order that deformation may take place by flowage. Since the temperature increases normally at the rate of 1° C. for 30 meters, and since in consequence of orogenic movements and igneous intrusions the increase in temperature with depth is often much more rapid than this, heat is a very important factor in the depth at which rock flowage occurs.

Since rock flowage may be in large measure by recrystallization, and recrystallization is dependent to a large extent upon the amount of water present, the greater the amount of water the more readily does deformation take place by flowage and therefore the less is the depth at which flowage begins.

The speed of deformation is also of very great consequence in limiting the upper part of the zone of flowage. The more rapid the deformation the greater the depth of the zone of flowage; the slower the deformation the more moderate its depth. Speed of deformation, and therefore the time consumed in a given deformation, is of very great importance. It is well known that a stress not sufficient to rupture a material or to appreciably deform it within a short time, if applied for a long time may produce important flowage deformation. The geologist must give this factor of time greater weight than scientists in any other subject. How important it is may be illustrated by the deformation of rock[a] as a result of placing it in an unusual position. In cemeteries marble slabs have been placed horizontally and supported at the ends; in the course of a score or more of years such slabs are found to have sagged in the middle a very considerable amount. This is illustrated in the cemetery of Jefferson City, Mo., where a slab about 1.8 meters long, .9 meter wide, and 5.08 centimeters thick,

[a] Van Hise, C. R., Principles of North American pre-Cambrian geology: Sixteenth Ann. Rept. U. S. Geol. Survey, pt. 1, 1896, p. 594.

suspended at the ends, has sagged 3.8 centimeters in the middle.[a] If it had been attempted to bend the slab at the outset to this extent, undoubtedly it would have been ruptured. The change in form without rupture is possible only by rock flowage, through a rupturing and differential movement of the solid particles with reference to one another, or by solution and redeposition—i. e., by granulation or recrystallization, or by the two combined.

On the assumptions (a) that the strength of the rocks is the same as at the surface, (b) that the rocks are all of the same kind, (c) that the temperature is the same as at the surface, (d) that the water present does not make any difference in the character of deformation, (e) that the rocks yield as readily by fracture as by flowage, (f) that the rocks break as readily by fracture when the deformation is slow as when it is rapid, and (g) that the rocks are among the strongest, I have calculated that the maximum depth of the upper part of the zone of flowage under mass-static conditions can not be greater than 12,000 meters. All of these assumptions, except the first, are in favor of great depth for the zone of flowage. It is explained (Chapter VIII, p. 672) that where rocks are under pressure in all directions the rigidity is probably greater than at the surface. Therefore the assumption that the rocks are no stronger below than at the surface might lead to too small a depth. However, the other assumptions would give too great a depth, because the great majority of rocks are not nearly so strong as the strongest, and many of them have only a small fraction of this strength; because the temperature increases with increase of depth, with orogenic movements, and with intrusives; because water is present in considerable quantity, and where this agent is available with higher temperatures the rocks are deformed by flowage rather than by fracture (see p. 188); and, finally, because the rocks are ordinarily deformed so very slowly that with a rather moderate pressure the deformation takes place by flowage rather than by fracture. I can see no way to determine to what extent these factors render the maximum depth calculated too great; nor can any estimate be made as to how far the factor (a) renders the maximum depth calculated too small; but I suspect that the various factors giving too great a depth are of far greater consequence than the one factor giving too small

[a] Winslow, A., An illustration of the flexibility of limestone: Am. Jour. Sci., 3d ser., vol. 43, 1892, pp. 133–134.

a depth. Since there is no theoretical way accurately to evaluate these factors and thus to calculate the maximum depth of the upper part of the zone of flowage, one can judge of its real depth only by observation in mountain areas where deep-seated rocks have been deformed when buried under an approximately determinable thickness of rocks and afterwards have been brought to the surface by denudation. From observation data I suspect the maximum depth calculated is much too great, perhaps twice too great even for the strongest rocks; and for the weaker rocks it is certain that the alterations characteristic of the zone of flowage occur at depths but a fraction of 10,000 or 12,000 meters.

The boundary between the zone of fracture and the zone of flowage is approximately the same as the boundary between the upper and lower physical-chemical zones if indeed it is not identical with it. We may therefore say that the upper physical-chemical zone, the zone of katamorphism, and the zone of fracture are synonymous terms, as are also the lower physical-chemical zone, the zone of anamorphism, and the zone of flowage. The reasons for the correspondence of the zone of fracture with the zone of katamorphism, and of the zone of flowage with the zone of anamorphism, are clear.

To the bottom of the zone of fracture the rocks are strong enough to support themselves, hence there is not pressure in all directions greater than the strength of the rocks, and openings may exist. The reactions may therefore take advantage of these spaces and fill them, thus expanding the volume of the rocks without lifting them or doing the mechanical work of rupturing them. The openings which may thus be utilized vary from those of supercapillary size, such as bedding partings, fault and joint openings, to subcapillary openings between the individual grains. In order to thus fill these spaces, no large amount of work must be done against pressure by the chemical agents, but in proportion as the spaces are filled it is more and more difficult for the reactions to occur requiring expansion of volume, as an increased amount of work must be done against pressure.

However, below the bottom of the zone of fracture, in the zone of flowage, the pressure in all directions is greater than the strength of the rocks. If supercapillary spaces be supposed to be present they would be closed by flow, unless this were prevented by occluded water or some other liquid or a gas which could not escape. If a reaction here occurs which

demands expansion of volume, it would be necessary to lift the entire superincumbent mass of rock, and this would require a vast amount of work. This work chemical affinity is usually not sufficiently strong to accomplish, therefore reactions do not take place which give increased volume; but on the contrary, the pressure forces reactions in the opposite sense from those in the upper zone, as a result of which the volume of a material is diminished. If the reactions diminishing volume can be of such a character as to liberate heat, this will occur; but frequently, in order to produce a decreased volume, chemical reactions must take place which absorb heat. In this paper on metamorphism the terms zone of katamorphism and zone of anamorphism are used, as being most serviceable. In structural work, however, the equivalent terms zone of fracturing and zone of flowage are more serviceable and therefore will there hold their place.

It may be seen on page 167, also on pages 766–768, that the passage from the zone of katamorphism to the zone of anamorphism is a gradation and not an abrupt change. The same is true of the change from the zone of fracture to the zone of flowage. (See pp. 187–189.) Therefore, whether the division of the outer crust of the earth into two zones be considered from the metamorphic point of view or from the structural point of view, there is a transition between the two.

CHAPTER V.

MINERALS.

In the previous chapters I have discussed the forces and agents of alteration, and the general nature of the alterations in the zones of anamorphism and katamorphism, including the two belts of the latter zone. We are now prepared to consider the particular alterations which affect the individual minerals in reference to these forces, agents, zones, and belts.

SECTION 1.—CHEMICAL AND MINERAL COMPOSITION OF THE KNOWN CRUST OF THE EARTH.

For convenience the outer part of the crust of the earth of which we have positive knowledge will be called the crust. Clarke,[a] for the purpose of considering the chemical composition of the outer part of the earth, confines this term "crust" to the part of the earth which extends from the tops of the mountains to 10 miles below sea level. He thinks it fair to assume that we may infer the approximate composition of this small part of the earth by the parts of it which may be observed at or near the surface.[b] The term "crust" in this treatise will be used in the restricted sense of Clarke. But in so using the term there is no intention to imply that there is any sharp division between the crust and the deeper part of the earth, to which the term "centrosphere" is applied.

Below is a table which gives the relative proportions of the twenty-one elements composing as much as 0.01 per cent of the crust of the earth as above defined, including the lithosphere, hydrosphere, and atmosphere, and also their atomic weights.[c]

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[a] Clarke, F. W., Relative abundance of the chemical elements: Bull. U. S. Geol. Survey No. 78, 1891, p. 34.

[b] Clarke, cit., pp. 34–37.

[c] Clarke, F. W., Analyses of rocks, laboratory of the United States Geological Survey, 1880–1899: Bull. U. S. Geol. Survey No. 168, 1900, p. 15.

Elements of the earth's crust.

Element.	Proportion.	Atomic weight.	Element.	Proportion.	Atomic weight.
	Per cent.			*Per cent.*	
Oxygen	47.02	15.88	Manganese	.07	54.57
Silicon	28.06	28.18	Sulphur	.07	31.83
Aluminum	8.16	26.91	Barium	.05	136.39
Iron	4.64	55.60	Strontium	.02	86.95
Calcium	3.50	39.76	Chromium	.01	51.74
Magnesium	2.62	24.10	Nickel	.01	58.24
Sodium	2.63	22.88	Lithium	.01	6.97
Potassium	2.32	38.82	Chlorine	.01	35.18
Titanium	.41	47.79	Fluorine	.01	18.91
Hydrogen	.17	1.00		100.00	
Carbon	.12	11.91			
Phosphorus	.09	30.79			

From this table it is seen that of the metallic elements aluminum, iron, magnesium, calcium, sodium, and potassium are the only ones which may be called abundant, and that of the nonmetallic elements oxygen and silicon are the only two which are abundant, although carbon, sulphur, and chlorine are very important, and still others of the nonmetallic elements, such as fluorine and phosphorus, are of considerable consequence. These elements combined, or rarely alone, as they occur in the natural state, are called minerals.

The more important minerals are classified into (1) elements, (2) oxides, (3) salts of the binary acids, and (4) salts of the ternary acids. Of the twenty-one elements above given, only oxygen, iron, nickel, sulphur, and carbon occur in the elemental form, and with the exception of oxygen the amounts thus occurring are insignificant. The free oxygen is mainly contained in the atmosphere, but large quantities are also included in the hydrosphere and lithosphere. The oxides comprise both hydrous and anhydrous minerals. Of the salts of the binary acids, the sulphides are of predominant importance, but the chlorides and fluorides are of some consequence. The salts of the ternary acids are the predominant minerals of the earth's crust. They include silicates, carbonates, titanates, phosphates, and sulphates. These compounds are mentioned in the order of their importance; indeed, the silicates are of dominating importance, but

next to them stand the carbonates, and the titanates and phosphates are subordinate. Therefore the acids of the silicates and carbonates—i. e., silicic and carbonic acids—are the great rock-forming acids.

The natural combinations of the elements, so far as they occur as important rock-making constituents, their systems of crystallization, chemical formulæ, molecular weights, logarithms of molecular weights, specific gravities, logarithms of specific gravities, molecular volumes (i. e., molecular weights divided by the specific gravities), and logarithms of molecular volumes, are given in tables below alphabetically arranged.

In the tables the chemical formulæ are usually those of the smallest possible molecules. There is no attempt to make the formulæ correspond with the real molecular structure of the minerals, since in the present state of knowledge it is quite impossible to do this. It therefore follows that the molecular weights, molecular volumes, and logarithms of the same in a given case are relative. The table should not be used to compare the absolute molecular weights and molecular volumes of the different minerals, as this would give wholly misleading results. For instance, actinolite, the second mineral in the table, varies in the amount of magnesium and iron so that it may have three special formulæ. These formulæ as written make the molecular weight of the mean molecule twice that of the smallest and that of the largest molecule four times that of the smallest. This results in similar variations in the molecular volumes and also considerable variations in the logarithms. Manifestly there are no such differences as these. Probably the true molecular weights and molecular volumes, and consequently the logarithms, are very close to one another. However, the numbers given in the table serve the purpose, as explained on pages 208–210, of calculating the changes of volumes when the particular varieties of the mineral actinolite represented by the formulæ are transformed to other minerals. These remarks as between the different varieties of actinolite apply equally well as between other minerals and their different varieties.

The letters D, G, H, and C, following formulæ or specific gravities, signify that the authorities from which the same are taken are, Dana, Groth, Hintze, and Clarke, respectively.

Rock-making minerals.

Mineral.	System.	Formula.	Molecular weight.	Logarithm of molecular weight.	Specific gravity.	Logarithm of specific gravity.	Molecular volume.	Logarithm of molecular volume.
Acmite (ægirite)	Monoclinic	$NaFe(SiO_3)_3$ (D, G)	230.12	0.3619544	3.525	0.5471591	65.282	0.8147953
		$Na_2Fe_2Si_4O_{12}$ (H).						
Actinolite	....do	$(MgFe)_8CaSi_4O_{12}$ (D, G, H).						
		(Mg : Fe : : 1 : 1) $Mg_3Fe_5Ca_2Si_8O_{24}$ (H)	925.18	.9662262	3.10	.4913617	298.445	.4748645
		(Mg : Fe : : 2 : 1) $CaMg_2FeSi_4O_{12}$ (G)	446.84	.6501520	3.10	.4913617	144.142	.1587903
		(Mg : Fe : : 3 : 1) $Mg_5Fe_3Ca_4Si_{16}O_{48}$	1,755.86	.2444899	3.10	.4913617	566.407	.7531282
Albite	Triclinic	$NaAlSi_3O_8$ (D, G)	261.37	.4172557	2.6350	.4207806	99.1916	.9964751
Allanite (orthite)	Monoclinic	$(CaFe)_2(AlOH)(AlCeFe)_2(SiO_4)_3$ (C, G)			3.85	.585461		
Allophane	Amorphous	$Al_2SiO_5+5H_2O$ (D)	250.80	.399347	1.87	.271842	134.22	.127505
Almandite	Isometric	$Fe_3Al_2Si_3O_{12}$ (C, D, H)	495.72	.6952364	4.05	.6074550	122.40	.0877814
Analcite	.....do	$Na_2Al_2Si_4O_{12}.2H_2O$ (D, G, H)	438.62	.6420884	2.255	.3531465	194.51	.2889419
Andalusite	Orthorhombic	Al_2SiO_5 (D, G)	161.40	.2079035	3.18	.5024271	50.7547	.7054764
Anhydrite	.....do	$CaSO_4$ (D)	135.11	.1306875	2.942	.4686427	45.9246	.6620448
Ankerite	Rhombohedral	$CaFe(CO_3)_2.CaMg(CO_3)_2$ (D)	397.42	.5992497	3.025	.4807254	131.379	.1185243
Anorthite	Triclinic	$CaAl_2Si_2O_8$ (D, G)	276.98	.4424484	2.75	.4393327	100.72	.0031157
Anorthoclase	Pseudomonoclinic	$mNaAl_2Si_3O_8.nKAl_2Si_3O_8$ (D)	592.50	.772688	2.585	.4124605	229.20	.3602215
	Triclinic	1 : 1						
Anthophyllite	Orthorhombic	$(MgFe)SiO_3$ (D).						
		(Mg : Fe : : 3 : 1) $Mg_3FeSi_4O_{12}$	431.18	.6346586	3.15	.4983106	136.883	.1363480
		(Mg : Fe : : 4 : 1) $Mg_4FeSi_5O_{15}$	531.10	.7251763	3.15	.4983106	168.6	.2358657
Apatite	Hexagonal	$(CaF)Ca_4(PO_4)_3$ (D, G)	500.64	.6995255	3.20	.5051500	156.45	.1943755
Aphrosiderite		$H_{10}(FeMg)_6(AlFe)_4Si_4O_{25}$ (G).						
		$H_{10}Fe_4Mg_2Al_4Si_4O_{25}$	897.96	.9532570	2.90	.4623980	309.641	.4908590
Aragonite	Orthorhombic	$CaCO_3$ (D)	99.31	.9969930	2.94	.4683473	33.779	.5286457
Arfvedsonite	Monoclinic	$(Na_2CaFe)_4Si_4O_{12}$.						
		$(CaMg)_2(AlFe)_4Si_2O_{12}$ (H)	920.20	.9638820	3.445	.5371892	267.11	.4266928
Augite	.....do	$Ca(MgFe)Si_2O_6$ with	215.50	.333447	3.4	.5314789	63.38	.8019681
		$(MgFe)(AlFe)_2SiO_6$ (H).						
		$CaMgSi_2O_6$ (D, G).						
Axinite	Triclinic	$HCa_2Al_2BSi_4O_{18}$ (C, D)	551.76	.7417502	3.2875	.5168658	167.836	.2248844
Bastite	Orthorhombic	$H_4(MgFe)_3Si_2O_9$	307.08	.4872515	2.6	.4149733	118.11	.0722782
		(Mg : Fe : : 3 : 1) $H_{16}Mg_9Fe_3Si_8O_{36}$	1,196.82	.0780288	2.6	.4149733	460.315	.6630555
Biotite (normal)	Monoclinic	$KHMg_3Al_2Si_3O_{12}$ (C)	416.94	.6200736	2.90	.4623980	143.7725	.1576756
Biotite-chlorite		$H_2Mg_4Al_2Si_3O_{12}.4(OH)$ (C)	494.84	.6944648	2.80	.4471580	176.729	.2473068

Rock-making minerals—Continued.

Mineral.	System.	Formula.	Molecular weight.	Logarithm of molecular weight.	Specific gravity.	Logarithm of specific gravity.	Molecular volume.	Logarithm of molecular volume.
Bronzite	Orthorhombic	$(MgFe)SiO_3$ (D, G).						
		Mg : Fe : : 3 : 1	431.18	0.6346583	3.25	0.5118834	132.64	0.1227749
		Mg : Fe : : 6 : 1	730.94	.8638820	3.25	.5118834	224.90	.3519986
		Mg : Fe : : 8 : 1	930.78	.9688476	3.25	.5118834	286.40	.4569642
Brookite	Orthorhombic	TiO_2 (D)	79.55	.9006402	3.975	.5993371	20.0126	.3013031
Brucite	Rhombohedral	$Mg(OH)_2$ (D)	57.86	.7623784	2.39	.3783979	24.2092	.3839805
Calcite	do	$CaCO_3$ (D)	99.31	.9969030	2.7135	.4335298	36.5985	.5634632
Cancrinite	Hexagonal	$H_6Na_6Ca(NaCO_3)_2Al_6Si_6O_{36}$ (D)	1,388.48	.1425396	2.46	.3909351	564.423	.7516045
Chabazite	Rhombohedral	$(CaNa_2)Al_2Si_4O_{12}+6H_2O$ (D, H).						
		Al_2 : Si : : 1 : 3.						
		Al_2 : Si : : 1 : 5.						
		$Ca_3Al_6(SiO_4)_3(Si_3O_8)_3.18H_2O$ (C)	1,512.42	.1796724	2.12	.3263359	713.406	.8533365
Chlorite	Monoclinic	$mH_4Mg_2Al_2SiO_9.nH_4Mg_3Si_2O_9$.						
Amesite	do	$H_4Mg_2Al_2SiO_9$ (D)	277.12	.4426679	2.71	.4329693	102.258	.0096983
Corundophilite	do	$H_{20}Mg_{11}Al_8Si_6O_{45}$ (D)	1,384.06	.1411549	2.90	.4623980	477.26	.6787569
Prochlorite	do	$H_{40}Mg_{23}Al_{14}Si_{13}O_{90}$ (D)	2,766.58	.4419433	2.87	.4578319	963.96	.9840614
Clinochlore	do	$H_{20}Mg_{12}Al_8Si_7O_{45}$ (D)	1,382.52	.1406714	2.715	.4337698	509.216	.7069016
Penninite	do	$H_8Mg_5Al_2Si_3O_{18}$ (D)	552.70	.7424895	2.725	.4353665	202.82	.3071230
		$H_{20}Mg_{13}Al_4Si_8O_{45}$ (D)	1,380.98	.1401874	2.725	.4353665	506.78	.7048209
Chloritoid	Monoclinic or triclinic	$H_2(FeMg)Al_2SiO_7$ (D, G)	250.76	.3992583	3.545	.5496162	707.36	.8496421
		(Small quantity of Mg.)						
Chlorophyllite	Monoclinic	$H_8(MgFe)_4Al_6Si_{10}O_{40}$ (C).						
		$(Mg : Fe : : 3 : 1)H_8Mg_6FeAl_8Si_{10}O_{40}$	1,268.18	.1031808	2.77	.4424798	457.827	.6607010
Chondrodite	do	$(MgF)_2Mg_3Si_2O_8$ (C).						
		$MgF_2Mg_3Si_2O_8$	317.62	.5019078	3.15	.4983106	100.832	.0035972
Chromite	Isometric	$FeCr_2O_4$ (D)	222.60	.3475252	4.445	.6478718	50.079	.6996534
Cimolite	Amorphous	$H_6Al_4(SiO_3)_9.3H_2O$ (C, D)	849.66	.9292462	2.24	.3502480	379.31	.5789982
Clinohumite	Monoclinic	$(MgF)_2Mg_7Si_4O_{18}$ (C).						
		$MgF_2Mg_7Si_4O_{16}$	597.42	.7762796	3.15	.4983106	189.657	.2779690
Corundum	Rhombohedral	Al_2O_3 (D)	101.46	.0062949	4.025	.6047659	25.2075	.4015290
Cummingtonite	Monoclinic	$(MgFe)SiO_3$ (D)	231.34	.3642517	3.21	.5065050	72.06	.8577467
Cyanite (disthene)	Triclinic	Al_2SiO_5 (D, G)	161.40	.2079035	3.615	.5581083	44.647	.6497952
Diaspore	Orthorhombic	$AlO(OH)$ (D, G)	59.67	.7757560	3.40	.5314790	17.550	.2442770
Diopside	Monoclinic	$MgCaSi_2O_6$ (D, G, H)	215.50	.3334473	3.290	.5171959	65.5015	.8162514
		$CaMgFeSi_3O_9$	346.92	.540229	3.29	.5171959	105.44	.0230331

Rock-making minerals—Continued.

Mineral.	System.	Formula.	Molecular weight.	Logarithm of molecular weight.	Specific gravity.	Logarithm of specific gravity.	Molecular volume.	Logarithm of molecular volume.
Dolomite	Rhombohedral	$CaMg(CO_3)_2$ (D)	182.96	0.2623562	2.8500	0.4548449	64.1965	0.8075113
		$(CaMg)CO_3$ (D)	123.41	.0913504				
Enstatite	Orthorhombic	$MgSiO_3$ (D)	99.92	.9996524	3.2	.5051500	31.225	.4945024
		$(MgSiO_3)_2$ (C, G).						
Epidote	Monoclinic	$mCa_2(AlOH)Al_2(SiO_4)_3.nCa_2(FeOH)Fe_2(SiO_4)_3$ (D) 6:1 Al:Fe::to 3:2	452.23	.6553598	3.38	.5289167	133.796	.1264431
Epistilbite	do	$H_4CaAl_2Si_6O_{13}+3H_2O$ (D, H)	606.14	.782580	2.25	.352183	269.39	.430397
Eucryptite	Hexagonal	$LiAlSiO_4$ (D, H)	125.58	.0989205	2.667	.4260230	47.0866	.6728975
Fayalite	Orthorhombic	Fe_2SiO_4 (D, G, H)	202.90	.3072820	4.1	.6127839	49.487	.6944981
		$n.Fe_2SiO_4$ (C).						
Fluorite	Isometric	CaF_2 (D)	77.58	.8897498	3.13	.4955443	24.786	.3942055
Forsterite	Orthorhombic	Mg_2SiO_4 (D)	139.90	.1458177	3.24	.5105450	43.179	.6352727
Garnet	Isometric	$R''_3R'''_2(SiO_4)_3$ (D) R″=CaMgFe″Mn″. R‴=AlFe‴(Mn‴)CrTi‴.			3.725	.5711263		
Gedrite	Orthorhombic	$(MgFe)_2Si_2O_6.MgAl_2SiO_6$ (H)	432.72	.6362072	3.15	.4983106	137.37	.1378966
Gehlenite	Tetragonal	$Ca_2Al_2Si_2O_{10}$ (D)	388.26	.5891227	2.985	.4749443	130.070	.1141784
Gibbsite	Monoclinic	$Al(OH)_3$ (D)	77.55	.8895818	2.35	.3710679	33.00	.5185139
Glsmondite	do	$Ca_3Al_6Si_2O_{24}.12H_2O$ (C)	1,045.50	.0193240	2.265	.3550682	461.59	.6642558
Glaucophane	do	$NaAlSi_2O_6.(FeMg)SiO_3$ (C) Mg:Fe::2:1.	935.55	.9710675	3.108	.4924810	301.01	.4785865
Glauconite	Amorphous	Composition variable (D)			2.3	.3617278		
Graphite	Rhombohedral	Carbon (D)	11.91	:0759118	2.16	.3344538	5.5139	.7414580
Grossularite	Isometric	$Ca_3Al_2Si_3O_{12}$ (C, D, G)	448.20	.6514719	3.605	.5569053	124.327	.0945666
Grünerite	Monoclinic	$FeSiO_3$ (D)	131.42	.1186615	3.713	.5697249	35.3946	.5489366
Gypsum	do	$CaSO_4.2H_2O$ (D)	170.87	.2326658	2.321	.3656751	73.619	.8669907
Halite	Isometric	NaCl (D)	58.06	.7638770	2.35	.3710679	24.7064	.3928091
					[a] 2.135	[a] .3293979		
Halloysite	Massive	$H_4Al_2Si_2O_9+aq.$ (D)			2.1	.3222190		
Haüynite	Isometric	$Na_2Ca(NaSO_4.Al)Al_2Si_3O_{12}$ (C, D, G) $(Na_2Ca)_5Al_6Si_6O_{24}S_2O_3$ (H).	559.58	.7478622	2.45	.3891661	228.40	.3586961
Hedenbergite	Monoclinic	$CaFeSi_2O_6$ (D, G, H)	247.00	.3926970	3.54	.5490033	69.774	.8436937
Hematite	Rhombohedral	Fe_2O_3 (D)	158.84	.2009599	[b] 5.225	[b] .7180863	30.400	.4828736

[a] Pure crystals.

[b] Of crystals.

Rock-making minerals—Continued.

Mineral.	System.	Formula.	Molecular weight.	Logarithm of molecular weight.	Specific gravity.	Logarithm of specific gravity.	Molecular volume.	Logarithm of molecular volume.
Hercynite	Isometric	$FeAl_2O_4$ (D)	172.94	0.2378955	3.98	0.5943926	44.005	0.6435029
Heulandite	Monoclinic	$H_4CaAl_2Si_6O_{18}+3H_2O$ (D, G, H)	606.14	.7825728	2.20	.342423	275.516	.4401498
Hornblende	do	Chiefly $Ca(MgFe)_3Si_4O_{12}$ with $(MgFe)_2(AlFe)_4Si_2O_{12}$ and some $Na_2Al_2Si_4O_{12}$ (H).						
		$Ca_2Mg_3Fe_2Si_8O_{24}(Mg_4Fe_2)(Al_2Fe_4)Si_6O_{36}$	2,311.22	.3638412	3.26	.5132176	708.96	.8506236
Humite	Orthorhombic	$(MgF)_2Mg_5Si_3O_{12}$ (C)	457.52	.6604101	3.15	.4983106	145.244	.1620995
Hydrargillite (gibbsite.)	Monoclinic	$Al(OH)_3$ (D)	77.55	.8895818	2.35	.3710679	33.00	.5185139
Hydrobiotite		$H_2Mg_2Al_2Si_3O_{12}.3H_2O$ (C)	432.76	.6362471	[a] 2.90	.4623980	149.228	.1738491
Hydromagnesite	Monoclinic	$Mg_2(CO_3)_2.2Mg(OH).3H_2O$ (D, G)	362.45	.5592481	2.1625	.3349561	167.607	.2242920
Hydronephelite	Hexagonal	$H\,Na_2Al_3Si_3O_{12}.3H_2O$ (C, D, G, H)	456.23	.6591838	2.263	.3546846	201.604	.3044992
Hydrophlogopite	Monoclinic	$H_3Mg_3AlSi_3O_{12}.3H_2O$ (C)	430.95	.6344269	[b] 2.303	.362295	187.12	.2721319
Hypersthene	Orthorhombic	$(MgFe)SiO_3$ (D).						
		3 : 1	431.18	.6346586	3.45	.5378191	124.979	.0968395
		Mg : Fe :: to nearly 1 : 1	231.34	.3642507	3.45	.5378191	67.055	.8264316
		$(FeMg)_2(SiO_3)_2$ (G).						
Ilmenite	Rhombohedral	$FeTiO_3$ (D)	151.03	.1790632	4.75	.6766936	31.796	.5023696
Iolite	Orthorhombic	$H_2(MgFe)_4Al_8Si_{10}O_{37}$ (C, D)						
		Mg : Fe :: 3 : 1 to 7 : 2	1,214.54	.0844118	2.63	.4199557	461.802	.6644561
Jadeite	Monoclinic	$NaAlSi_2O_6$ (D)	201.43	.3041242	3.34	.5237465	60.308	.7803777
Kaolin	do	$H_4Al_2Si_2O_9$ (C, D)	257.10	.4101102	2.615	.4174717	98.3174	.9926385
Laumontite	Monoclinic	$H_4CaAl_2Si_4O_{14}.2H_2O$ (D, G)	468.38	.6705983	2.305	.3626709	203.202	.3079274
Leucite	Isometric	$KAlSi_2O_6$ (D)	217.37	.3371996	2.475	.3935752	87.8263	.9436244
		$K_2Al_2Si_4O_{12}$ (H)						
Limonite	Not crystallized	$2Fe_2O_3.3H_2O$ (D).						
		$Fe_4O_9H_6$	371.32	.5697483	3.800	.5797836	97.716	.9899647
Magnesite	Rhombohedral	$MgCO_3$ (D)	83.65	.9224659	3.06	.4857214	27.3366	.4367445
Magnetite	Isometric	Fe_3O_4 (D)	230.32	.3623317	5.174	.7138264	44.515	.6485053
Malacon	Tetragonal	$H_2Zr_3Si_3O_{13}$ (C)	562.14	.7498445	3.905	.5916210	143.954	.1582235
Marcasite	Orthorhombic	FeS_2 (D)	119.26	.0764948	4.875	.6879746	24.4636	.3885202
Margarite	Monoclinic	$H_2CaAl_4Si_2O_{12}$ (C, D, G)	396.32	.5980460	3.035	.4821587	130.583	.1158873
Marialite	Tetragonal	$Na_4Al_3Si_9O_{24}Cl$ (C, D, G, H)	842.17	.9253998	2.566	.4092567	328.204	.5161431
Meionite	do	$Ca_4Al_6Si_6O_{25}$ (C, D, G, H)	886.58	.9477179	2.72	.4345689	325.948	.5131490

[a] Average of biotite.

[b] Kerrite.

Rock-making minerals—Continued.

Mineral.	System.	Formula.	Molecular weight.	Logarithm of molecular weight.	Specific gravity.	Logarithm of specific gravity.	Molecular volume.	Logarithm of molecular volume
Melanite	Isometric	$Ca_3Fe_2Si_3O_{12}$ (G)	505.58	0.7037899	3.85	0.5854607	131.32	0.1183292
Melilite	Tetragonal	$(CaMgNa_2)_6(AlFe)_2Si_5O_{19}$ (H)	680.51	.8328344	3.00	.4771213	226.83	.3557131
Mesolite	Monoclinic and triclinic	$H_8Na_2CaAl_6Si_9O_{24}.H_2O$ (C, G)	769.24	.8860619	2.29	.3598355	335.913	.5262264
Microcline	Triclinic	$KAlSi_3O_8$ (D, G)	277.31	.4429655	2.555	.4073909	108.536	.0355746
Muscovite	Monoclinic	$(HK)AlSiO_4$ (D)						
		$(H:K::2:1)\ H_2KAl_3Si_3O_{12}$ (C, G)	396.65	.5984075	2.88	.4593925	137.726	.139051
Natrolite	Rhombohedral	$Na_2Al_2Si_3O_{10}.2H_2O$ (D, G, H)	378.68	.5782724	2.225	.3473300	170.198	.2309424
	Orthorhombic	(D)						
Nephelite	Hexagonal	$(NaK)_8Al_8Si_9O_{34}$ (H)	1,255.34	.0987618	2.60	.4149733	482.82	.6837885
		$K_2Na_6Al_8Si_9O_{34}$ (D)	1,223.74	.0876945	2.60	.4149733	470.67	.6727212
		$NaAlSiO_4$ (C)	141.49	.1507257	2.60	.4149733	54.4192	.7357524
		$KNa_3Al_4Si_4O_{16}$	581.90	.7648484	2.60	.4149733	223.808	.3498751
Newtonite	Rhombohedral	$H_8Al_2Si_2O_{11}+H_2O$ (D)	310.74	.492397	2.37	.374748	131.11	.117649
		H_5AlSiO_5 (C).						
Noselite	Isometric (perhaps tetragonal).	$Na_4(NaSO_4Al)Al_2Si_3O_{12}$ (D)	565.58	.7524940	2.325	.3664230	243.26	.3860710
Octahedrite (anatase)	Tetragonal	TiO_2 (D)	79.55	.9006402	3.885	.5893910	20.4762	.3112492
Olivine (chrysolite, peridot)	Orthorhombic	$(MgFe)_2SiO_4$ 1:1 (D)	171.38	.2339094	3.4	.531479	50.40	.7024310
		Mg:Fe:: 16:1, 12:1, to 3:1 $Mg_3FeSi_2O_8$	311.30	.4931791	3.32	.5211381	93.765	.9720410
		Mg:Fe:: 2:1 $Mg_4Fe_2(SiO_4)_3$ (C)	482.70	.6836773	3.57	.5526682	135.21	.1310091
Opal	Amorphous	$SiO_2.nH_2O$ (D, G) ($\frac{1}{8}H_2O$)	62.92	.7987887	[a] 2.15	.3324385	29.2652	.4663502
Orthoclase	Monoclinic	$KAlSi_3O_8$ (D, G)	277.31	.4429655	2.57	.4099331	107.903	.0330324
Ottrelite	Monoclinic or triclinic	$H_2(FeMn)Al_2Si_2O_9$ (D, G)	620.37	.7926510	3.545	.5496160	174.99	.2430350
Paragonite	Monoclinic	$H_2NaAl_3Si_3O_{12}$ (C, D, G)	380.71	.5805943	2.84	.4533183	134.053	.1272760
Parankerite	Rhombohedral	$CaFe(CO_3)_2.2CaMg(CO_3)_2$ (D)	580.38	.7637130	3.075	.4878451	187.741	.2758679
Pectolite	Monoclinic	$HNaCa_2Si_3O_9$ (C, D)	330.86	.5196443	2.73	.4361626	121.19	.0834817
Perovskite	Isometric or pseudo-isometric.	$CaTiO_3$ (D)	135.19	.1309446	4.028	.6050895	33.5626	.5258551
Phillipsite	Monoclinic	$Al_6Ca_2K_2Si_{12}O_{36}.14H_2O$ (C)	1,478.78	.1699035	2.20	.3424227	672.172	.8274808
Phlogopite	do	$KH_2Mg_3AlSi_3O_{12}$ (C)	415.13	.6181841	2.815	.4494784	147.47	.1687057
Phlogopite-chlorite	do	$H_5Mg_6AlSi_3O_{12}.6(OH)$ (C)	550.89	.7410651	[b] 2.649	.423082	207.96	.3179831

[a] Pure.

[b] Variety of penninite.

Rock-making minerals—Continued.

Mineral.	System.	Formula.	Molecular weight.	Logarithm of molecular weight.	Specific gravity.	Logarithm of specific gravity.	Molecular volume.	Logarithm of molecular volume.
Picotite	Isometric	$(MgFe)(AlCr)_2O_4$ (D).						
		$MgFeAl_2Cr_2O_8$	364.04	0.6611486	4.08	0.6106602	89.225	0.9504884
Piedmontite	Monoclinic	$Ca_2(AlOH)(AlMn)_2(SiO_4)_3$ (C, D, G)	915.99	.9618912	3.404	.5319900	269.09	.4299012
Pinite	Massive	Close to muscovite (D)			2.775	.443263		
Piconaste	Isometric	$(MgFe)(AlFe)_2O_4$ (D, G).						
		$MgFeAl_2Fe_2O_8$	371.76	.5702627	3.55	.5502284	104.72	.0200843
Potassium carbonate		K_2CO_3	137.19	.1373225	2.29	.3598355	59.9083	.7774870
Prehnite	Orthorhombic	$H_2Ca_2Al_2Si_3O_{12}$ (C, D)	410.44	.6132497	2.875	.4586378	142.762	.1546119
Pyrite	Isometric	FeS_2 (D)	119.26	.0764948	5.025	.7011361	23.7333	.3753587
Pyrope	do	$Mg_3Al_2Si_3O_{12}$ (C, D)	401.22	.6033826	3.725	.5711263	107.71	.0322563
Pyrrhotite	Hexagonal	$Fe_{11}S_{12}$ chiefly (D)	993.56	.9971941	4.61	.6637009	215.523	.3334932
Quartz	Rhombohedral	SiO_2 (D)	59.94	.7777167	[a]2.6535	.4238191	22.589	.3538976
Riebeckite	Monoclinic	$2NaFe(SiO_3)_2.FeSiO_3$ (D)	591.66	.7720724	3.3	.5185140	179.29	.2535584
Rutile	Tetragonal	TiO_2 (D)	79.55	.9006402	4.215	.6247976	18.873	.2758426
Sahlite	Monoclinic	$(MgFe)CaSi_2O_6$ (G, H).						
		$MgFeCa_2Si_4O_{12}$	462.50	.6651117	3.325	.5217916	139.098	.1433201
		$(Mg:Fe::3:1)Mg_3FeCa_4Si_8O_{24}$	893.50	.9510946	3.325	.5217916	268.722	.4293030
Scolecite	do	$CaAl_2Si_3O_{10}+3H_2C$ (C, D, G)	390.56	.5916878	2.28	.3579348	171.299	.2337530
		$CaAl_2Si_3O_{10}.2H_2O+H_2O$ (H).						
Serpentine	do	$H_4Mg_3Si_2O_9$ (C, D)	275.58	.4402477	2.575	.4107772	107.021	.0294705
		$H_4Mg_2FeSi_2O_9$	307.08	.4872515	2.575	.4107772	119.255	.0764743
Siderite	Rhombohedral	$FeCO_3$ (D)	115.15	.0612639	3.855	.5860244	29.8703	.4752395
Sillimanite	Orthorhombic	Al_2SiO_5 (D, G)	161.40	.2079035	3.235	.5098743	49.8918	.6980292
		$(Al_2SiO_5)_3$ (C).						
Sodalite	Isometric	$NaCl.3NaAlSiO_4$ (C, D)	482.53	.6835243	2.22	.3463530	217.356	.3371713
Spessartite	do	$Mn_3Al_2Si_3O_{12}$ (C, D, H)	492.63	.6925209	4.15	.6180481	118.706	.0744728
Spinel	do	$MgAl_2O_4$ (D, G)	141.44	.1505722	3.8	.5797836	37.221	.5707886
Spodumene	Monoclinic	$LiAl(SiO_3)_2$ (D, G)	185.52	.2683907	3.165	.5003737	58.616	.7680170
Beta-spodumene		$LiNaAl_2Si_4O_{12}$ (H)	386.95	.5876549	2.6465	.4226719	146.212	.1649830
Staurolite	Orthorhombic	$HFeAl_5Si_2O_{13}$ (G)	453.95	.6570080	3.71	.5693739	122.359	.0876341
		(Mg replaces small part of FeO; Fe_2O_3 small part of Al_2O_3).						
Stilbite (desmine)	Monoclinic	$Ca_3Al_6(Si_3O_8)_6.18H_2O$ (C)	1,872.06	.2723197	2.1495	.3323374	870.928	.9399823
Talc	Orthorhombic or monoclinic.	$H_2Mg_3Si_4O_{12}$ (C, D, G)	377.58	.5770090	2.75	.4393327	137.302	.1376763

[a] In crystals.

Rock-making minerals—Continued.

Mineral.	System.	Formula.	Molecular weight.	Logarithm of molecular weight.	Specific gravity.	Logarithm of specific gravity.	Molecular volume.	Logarithm of molecular volume.
Thomsonite	Orthorhombic	$Ca_3Al_6Si_6O_{24}.7H_2O$ (C)	956.10	0.9805033	2.35	0.3710679	406.851	0.6094354
		$(Na_2Ca)Al_2Si_2O_8+\frac{5}{2}H_2O$ (D, G).						
		Na : Ca : : 3 : 1						
		1:1 $Na_2CaAl_4Si_4O_{16}.5H_2O$	649.36	.8124855	2.35	.3710679	276.323	.4414176
Titanite (sphene)	Monoclinic	$CaTiSiO_5$ (D, G)	195.13	.2903240	3.48	.5415792	56.072	.7487448
Topaz	Orthorhombic	$Al_2F_2SiO_4$ (C, H)	183.34	.2632573	3.5	.5440680	523.83	.7191893
		$Al_2(F_2O)SiO_4$ (D, G).						
Tourmaline	Rhombohedral	$R'_6SiO_5=R''_2SiO_5=R'''_2SiO_5$ (D)	.....	.....	3.09	.4899585	.....	.....
		R′=Na, Li, K; R″=Mg, Fe, Ca; R‴=Al, B, Cr, Fe.						
Tremolite	Monoclinic	$CaMg_3Si_4O_{12}$ (C, D, G)	415.34	.6184038	3.000	.4771213	138.447	.1412825
Tridymite	Hexagonal or pseudo-hexagonal.	SiO_2	59.94	.7777167	2.305	.3626709	260.043	.4150458
Trisilicic anorthite	.....	$Ca_3Al_6(Si_3O_8)_6$ (C)	1,550.22	.1903933	.....	.....	.....	.....
Uvarovite	Isometric	$Ca_3Cr_2Si_3O_{12}$ (D, G)	497.86	.6971072	3.465	.5397032	143.682	.1574040
Vesuvianite	Tetragonal	$HR''_6Al_3Si_5O_{21}$ (C)	794.67	.9001868	3.40	.5314789	233.726	.3687079
		R″=Ca						
Wollastonite	Monoclinic	$CaSiO_3$ (D, G, H)	115.58	.0628827	2.850	.4548449	40.5544	.6080378
		$(CaSiO_3)_3$ (C).						
Zeolite (analcite)	Isometric	$Na_2Al_2Si_4O_{12}.2H_2O$ (G)	438.62	.6420884	2.255	.3531465	194.51	.2889419
Zircon	Tetragonal	$ZrSiO_4$ (C, D, G)	181.42	.2586852	4.69	.6711728	38.6823	.5875124
Zoisite	Orthorhombic	$Ca_2(AlOH)Al_2(SiO_4)_3$ (C, D, G)	452.23	.6553594	3.31	.5198280	136.6255	.1355314
		$H_2Ca_4Al_6Si_6O_{26}$ (H)	904.46	.9563894	3.31	.5198280	273.251	.4365614

SECTION 2.—GENERAL NATURE OF ALTERATIONS.

Minerals may be altered (1) without chemical change and (2) with change of chemical composition.

ALTERATION WITHOUT CHANGE IN CHEMICAL COMPOSITION.

The alterations which occur without changes in chemical composition are (a) molecular rearrangement and (b) simple recrystallization.

MOLECULAR REARRANGEMENT.

Molecular rearrangement alone means passage from one crystalline form to another crystalline form. Such change of form may result from changed physical conditions, as, for instance, change in temperature or pressure or movement. As an example of molecular rearrangement due to change of temperature may be mentioned leucite, which crystallizes from a hot magma in the regular system, but which changes upon cooling to ordinary temperatures to a complex twinned anisometric form. An example of a change due to pressure is furnished by orthoclase, which is said for this reason to alter to microcline.[a] Molecular readjustments such as above are simply changes of form, and are therefore called paramorphism.

SIMPLE RECRYSTALLIZATION.

Simple recrystallization usually but probably not always occurs through the medium of a certain amount of water, which is able to take material into solution and deposit it from solution. Changing pressure and comparatively high temperatures are favorable conditions for such recrystallization. Perhaps the most common example of recrystallization without chemical change is that of the transformation of amorphous or finely crystalline calcium carbonate to crystalline or more coarsely crystalline calcium carbonate, such as occurs in limestones and marble. This process has been called marmorosis. Another instance of recrystallization without change in chemical composition which takes place, on an extensive scale, is alteration of flinty or finely crystalline quartz to coarsely crystalline quartz.

ALTERATION WITH CHANGE IN CHEMICAL COMPOSITION.

Alterations with chemical change may take place (1) without the addition or subtraction of material or (2) with the addition or subtraction

[a] Dana, J. D., A system of mineralogy, Descriptive mineralogy by E. S. Dana, Wiley & Sons, New York, 6th ed., 1892, p. 318.

of material. For either of these changes the presence of water is required in most instances, the alterations taking place through solution and redeposition, although it is not impossible that solids may act upon one another to an important extent without the help of water.

ALTERATION WITHOUT ADDITION OR SUBTRACTION OF MATERIAL.

In the changes which occur under this case the material moves only short distances. Such changes may be (a) a crystallization of an amorphous substance or (b) interior alteration of mineral particles.

An instance of the crystallization of an amorphous substance is furnished by the devitrification of glass. In this alteration the uniform homogeneous solid glass changes into a heterogeneous crystalline solid, the different mineral particles of which have differing compositions. This involves segregation of the different elements in various proportions into the different minerals. It is therefore clear that the materials have moved very short distances.

Interior alteration of mineral particles is effected by the change of one mineral into two or more minerals. This is illustrated by the change of pyrope into enstatite, spinel, and quartz; the change of pyrope into hypersthene, spinel, and quartz; the change of spodumene into eucryptite and albite; the change of almandite into hypersthene, spinel, and quartz; and the change of titanite into perovskite and quartz.

ALTERATION WITH ADDITION OR SUBTRACTION OF MATERIAL.

The changes which take place with the addition or subtraction of material may vary from those which involve the slightest addition or subtraction to complete substitution. The added material may come from afar or from the adjacent mineral particles. The subtracted material may enter into an adjacent mineral particle or may be transported great distances before entering into a new mineral. Reactions between adjacent minerals may produce new minerals. Two or more minerals may unite to produce a single mineral. For example, olivine and quartz may pass into anthophyllite; nephelite and halite into sodalite; albite and halite into marialite. Or two or more minerals may unite to produce two or more new minerals. For example, rutile and magnetite may pass into ilmenite and hematite; diopside and magnetite into tremolite and calcite; sahlite, siderite, and magnesite into actinolite and calcite; augite, siderite, and

magnesite into hornblende and calcite; or the reverse of this, hornblende and calcite into augite, siderite, and magnesite.

The changes here belonging are by far the most numerous and important of the various classes; indeed, are vastly more important than all of the other classes together. By far the greater number of reactions written out on the succeeding pages for the alterations of the various minerals fall under this heading.

The more important of these alterations, considered from the point of view of the nonmetallic elements, may be classified into:

(1) Oxidation.
(2) Deoxidation.
(3) Hydration.
(4) Dehydration.
(5) Carbonation.
(6) Decarbonation.
(7) Silication.
(8) Desilication.
(9) Silicification.
(10) Desilicification.

Less important reactions are:

(11) Sulphidation.
(12) Desulphidation.
(13) Sulphation.
(14) Desulphation.
(15) Titanation.
(16) Detitanation.
(17) Phosphation.
(18) Dephosphation.
(19) Chloridation.
(20) Dechloridation.
(21) Fluoridation.
(22) Defluoridation.
(23) Boration.
(24) Deboration.

A number of these reactions are of small consequence so far as the alterations of rocks are concerned; but all are important with reference to the development of minerals, and especially in reference to economic products. This phase of the subject in reference to the metallic products is treated in Chapter XII.

(1) Oxidation is the addition of oxygen. Frequently the added oxygen is substituted for another element, often sulphur.

(2) Deoxidation is the subtraction of oxygen. Often the subtracted oxygen is replaced by another element—for instance, sulphur.

(3) Hydration is the addition of water, producing hydroxides.

(4) Dehydration is the subtraction of water from hydroxides. When carried to completion, anhydrous compounds are formed.

(5) Carbonation is the union of carbonic acid and base, or the substitution of carbonic acid for another combined acid, in either case producing carbonates. The oxide with which carbonic acid most frequently unites is

iron oxide. Carbonic acid may replace any of the other ternary rock-forming acids, including silicic, titanic, and phosphoric, and thus become united with any of the important bases. The carbonation of the silicates is of fundamental importance. The carbonation of the titanates and phosphates is unimportant.

(6) Decarbonation is the separation of carbonic acid from a base without the addition of other compounds, or with the substitution of another acid for the carbonic. The most frequent substituted acid is silicic.

(7) Silication is the union of silicic acid and base, or the substitution of silicic acid for a combined acid, in either case producing silicates. The only important oxide with which silicic acid unites as a rock-forming constituent is iron oxide. Silicic acid may replace carbonic, titanic, or phosphoric acid, thus becoming united with any of the bases with which it can combine. The silication of the carbonates is of fundamental importance. The silication of the titanates and phosphates is unimportant.

(8) Desilication is the separation of silicic acid and bases without the addition of other compounds, or with the substitution of another acid for the silicic acid. The most frequent acid substituted is carbonic.

(9) Silicification involves the addition of silica without union with bases. The added silica may or may not replace other compounds.

(10) Desilicification involves the subtraction of free silica. The subtracted silica may or may not be replaced by other compounds.

(11) Sulphidation is the union of sulphur with a metal forming sulphides. Added sulphur may be substituted for another element, usually oxygen.

(12) Desulphidation involves the subtraction of sulphur. Generally the subtracted sulphur is replaced by another element, usually oxygen.

(13) Sulphation is the union of sulphuric acid with base or the substitution of sulphuric acid for another combined acid, in either case producing sulphates.

(14) Desulphation is the separation of sulphuric acid and base, or the substitution of another acid for the sulphuric.

(15) Titanation is the union of titanic acid with base, or the substitution of titanic acid for another combined acid, in either case producing titanates.

(16) Detitanation is the separation of titanic acid and base, or the substitution of another acid for the titanic.

(17) Phosphation is the union of phosphoric acid with base, or the substitution of phosphoric acid for another combined acid, in either case producing phosphates.

(18) Dephosphation is the separation of phosphoric acid and base, or the substitution of another acid for the phosphoric acid.

(19) Chloridation is the addition of chlorine, forming chlorides.

(20) Dechloridation is the subtraction of chlorine, destroying chlorides.

(21) Fluoridation is the addition of fluorine, forming fluorides.

(22) Defluoridation is the subtraction of fluorine, destroying fluorides.

(23) Boration is the union of boric acid with base, or the substitution of boric acid for another combined acid, in either case producing borates.

(24) Deboration is the separation of boric acid and base, or the substitution of another acid for the boric.

GENERAL STATEMENTS.

The foregoing processes are seen to be in pairs, in each case one of a pair being the reverse of the other. That is, deoxidation is the reverse of oxidation, dehydration is the reverse of hydration, etc. Moreover, one of the processes of a pair is in several of the cases frequently the complement of that of another pair. To illustrate, the processes of the following pairs are often complementary of each other, viz, oxidation and desulphidation, sulphidation and deoxidation, carbonation and desilication, silication and decarbonation. By complement is meant that one takes place simultaneously with the other, and that the two may really be one chemical reaction. In such a case the change may be considered from either of two points of view. To illustrate, the process of carbonation may be also a process of desilication, and the process of silication may be also a process of decarbonation. In general the process is named on the basis of the substance added rather than that subtracted, for such substance is the active agent which drives off the other and takes it place. It has been shown (pp. 168, 170–181) that for several reactions one of a pair is particularly characteristic for one of the zones of metamorphism. To illustrate, oxidation and its complement desulphidation, carbonation and its complement desilication, and hydration are particularly characteristic of the zone of katamorphism; sulphidation and its complement deoxidation, silication and its complement decarbonation, and dehydration are particularly characteristic of the zone of anamorphism.

SECTION 3.—ROCK-MAKING MINERALS.

MANNER OF TREATMENT.

GENERAL STATEMENTS.

In this treatise only the principal rock-forming minerals will be considered. The point of view is not that of mineralogy but that of metamorphism. So far as it seems advisable without too much repetition, I shall consider each mineral in reference to the following:

(1) Its composition, crystallization, specific gravity, and source, so far as it is a rock-making mineral; but its occurrence in veins will not be considered.

(2) The minerals into which it may pass, giving their crystallizations, specific gravities, and compositions.

(3) The chemistry and physics of the processes of change, including the volume relations.

(4) The natural conditions under which the changes occur, and the causes of the changes.

With many minerals this outline can be carried out nearly to completion. With others the present state of knowledge is such that it can be only very incompletely done. Consequently there is great variation in the satisfactoriness of the discussion of the different minerals. When the treatment of each of the minerals from these various points of view can be carried out we shall have an interlocking system by which each mineral is considered in its most important metamorphic connections. To a certain extent the plan involves repetitions, but in each case the important facts which concern an individual mineral are brought together. The method of treatment proposed seems advisable, for many minerals are both primary and secondary, and only by considering each mineral from both points of view is it possible to understand the causes of the changes as well as the changes themselves. Ordinarily the latter only are considered. When one of the sources of a mineral is the alteration of another the exact reactions concerned in the change are not given under the former, but may be found by referring to the latter mineral which is mentioned as its source. Ordinarily, however, qualitative statements are made. To illustrate, a source of limonite is siderite. The reactions involved in this change are to be found under siderite, not under limonite; but under

the latter mineral the statement is made that the change generally involves liberation of heat and decrease of volume. But when a mineral is derived by precipitation from a solution, or results by the combination of several minerals, it is necessary to consider the chemistry and physics of the change in connection with the sources, for otherwise this important part of the history of metamorphism of minerals would be omitted.

In discussing the sources of a mineral when it is derived from other minerals the natural conditions of the alterations are not given, but may be found by referring to the minerals from which the one under discussion is derived. But where a mineral is derived by the interaction or union of several other minerals the natural conditions are discussed under the source of the mineral, for otherwise this part of the subject would be omitted.

As this treatise was originally planned it was designed to include the heat and volume changes with the chemical reactions. But with the present state of knowledge of the heat relations in chemical transformations the first has been found impracticable. While very few quantitative results can be given, in many cases it is possible to make a qualitative expression of the heat reaction. To illustrate, the heat of combination of calcium is far greater than that of iron in all analogous compounds in which determinations have been made; but such determinations have not been made with reference to the silicates. Where calcium is replaced by iron in the alteration of the silicates it is inferred that a considerable amount of heat is absorbed, though the exact amount can not be specified. Vice versa, where iron is replaced by calcium, a considerable amount of heat is liberated. Of course, in each reaction the other chemical combinations which occur simultaneously should be considered, for they constitute a part of the chain, and in obtaining a correct end result their effects are vital. If, for instance, a salt of iron and a salt of calcium interchange acids, no general statement can be made as to the heat reaction. Therefore, if at the same time the iron replaces the calcium the calcium unites with an acid which was before in combination with the iron, the inference above given as to absorption of heat can not be made.

For the calculation of the volume changes, the equations of the chemical reactions written out by me and the specific gravities of the minerals, taken from the standard Mineralogies, were turned over to Mr. A. T. Lincoln, who made the numerical computations. Subsequently Mr. R. M. Chapman

repeated the work in order to verify it. The following well-known principle was employed:

The volume of the original compound is to the volume of the compound produced directly as their molecular weights and indirectly as their specific gravities.

Under this general principle are two cases:

Case 1. Where one solid compound alters into another solid compound. This case is illustrated by the well-known changes of limestone to dolomite. In this change we have $2CaCO_3$ replaced by $MgCa(CO_3)_2$. The molecular weight of $2CaCO_3$ is 198.62. The molecular weight of $MgCa(CO_3)_2$ is 182.96. The specific gravity of calcite may be taken as 2.7135; of dolomite, as 2.85. The compound proportion is therefore as follows:

$$V : V^1 :: \begin{matrix} 198.62 : 182.96 \\ 2.85 : 2.7135 \end{matrix}$$

or the volume of the dolomite is 87.70 per cent of that of the calcite; or, therefore, there is a decrease in volume of 12.30 per cent.

Case 2. This has three phases: (a) where two or more solid compounds unite to produce a single solid compound; (b) where a single solid compound breaks up, producing two or more compounds, and (c) where two or more solid compounds unite to produce two or more solid compounds. In this case the method of calculation is slightly different from case 1. The molecular weights of each of the compounds represented in the equations are divided by the specific gravities of the respective compounds. This gives their relative volumes. In phase (a) the volume of the resultant single compound is divided by the sum of the volumes of the producing compounds, and this gives the percentage of change. In phase (b) the sum of the volumes of the resultant compounds is divided by the volume of the original compound. In phase (c) the sum of the volumes of the resultant compounds is divided by the sum of the volumes of the original compounds. These different phases are so similar in method that it is necessary only to illustrate one of them. The first phase is illustrated by the formation of wollastonite by the union of calcite and quartz, the reaction being:

$$CaCO_3 + SiO_2 = CaSiO_3 + CO_2.$$

The molecular weights of the three solid compounds are, respectively,

99.31, 59.94, and 115.58. Their specific gravities are 2.7135, 2.6535, and 2.85, respectively. The volume of the wollastonite is, therefore:

$$\frac{115.58}{2.85} \div \left(\frac{99.31}{2.7135} + \frac{59.94}{2.6535} \right) = 0.685$$

That is, the decrease in volume in this case of silication of calcite is 31.5 per cent.

In order to expedite the laborious numerical calculations of the volume relations for the very numerous alterations, Mr. Lincoln completed the table on pp. 195–201 by adding the molecular weights, the logarithms of the molecular weights, the logarithms of the specific gravities, the molecular volumes, and the logarithms of the molecular volumes of each of the minerals. These determinations have been carefully verified by Mr. Chapman, and may be used to check the volume changes given in the succeeding pages, and also to make additional volume calculations.

In calculating the volume relations, unless otherwise specified, the compounds on both sides of the equations are regarded as solid except those which by themselves independent of the solvents are liquids or gases, such as H_2O and CO_2. All such compounds are supposed to be added in the solutions or to be taken away by the solutions, and therefore are not taken into account in the volume calculations. In general these liquid and gaseous compounds do undoubtedly escape in large measure, although in some cases they are confined as inclusions within the minerals formed. (See p. 678.)

Where +k is added to the equation, this signifies that heat is liberated; where —k appears, this means that heat is absorbed by the reaction.

No claim is made that the equations which are written in the following pages exactly represent the changes that take place in the alterations of the various minerals into other minerals Indeed, the probability is that not half exactly represent the facts; for the great majority of the reactions are more complicated than written, and in many cases substances in the solutions or as solids not taken into account are concerned. Since these are the facts, the question may be asked why the equations are written.

The answer is, first, that at some time the attempt must be made to give a first approximation to quantitative exactness in the alteration of minerals. The equations found on the following pages represent such an attempt. Before the appearance of this treatise scarcely more than a score of mineral

alterations have been expressed by chemical equations, and in fewer still have the volume relations been calculated. Second, the imperfect equations herein contained will be sure to lead to closer investigations of the nature of the alterations, and to improved equations representing them. Thus the progress of science will be promoted by the set of equations here given, even if the great majority of them are defective. Third, it is believed that when a more nearly correct set of equations is written it will be found that the large majority of the equations herein contained substantially represent the facts, and consequently that the volume changes are in most cases roughly approximate. Many of them may be changed by a few per cent one way or the other; but the sign of few will be changed, and this is the fundamental point in reference to the zones in which the alterations occur.

The weakest point in the accuracy of the volume reactions is not found in the chemical equations, but in the inexactness of the specific gravities of the minerals as given in the text-books. For most minerals there is a considerable range of specific gravity given; and with the exception of one or two minerals, such as calcite and quartz, it is impossible to ascertain the exact specific gravity of the pure minerals. In the table the mean between the two best determined extremes is given as the best approximation available of the specific gravities of the pure minerals. For most minerals these extremes are taken from Dana's System of Mineralogy.

The facts as to the occurrences and alterations of the various minerals given in the following pages are largely taken from the standard text-books of mineralogy and petrology, and especially from Dana's great System of Mineralogy. The information available is especially imperfect as to the manner in which the complex minerals, and particularly the complex silicates, break up into simpler compounds in the belt of weathering. As explained fully in the following chapter, this is a general process. For the better known of these changes equations are written, but no attempt is made to express by equations the manner in which many of the minerals decompose and degenerate, because so little exact information is available upon which to base such equations.

As already stated, only those minerals will be considered which are important rock-making constituents. It is impracticable at the present time to consider the physical-chemistry of the rarer minerals.

Following the ordinary classification, the abundant rock-making constituents may be considered under the headings: Native Elements, Sulphides, Fluorides, Oxides, Carbonates, Silicates, Titanates, Phosphates, and Sulphates.

NATIVE ELEMENTS.

GRAPHITE.

Graphite:
Crystallized carbon (C).
Rhombohedral.
Sp. gr. 2.09–2.23; av. 2.16.

Occurrence.—Graphite occurs as a very widely disseminated constituent in the extremely metamorphosed sedimentary rocks, which in their original condition contained carbonaceous material. It is especially prevalent in scales in the marbles, schists, and gneisses. In some instances the original beds were so heavily carbonaceous as to give considerable layers a large percentage of which is graphite. Such layers are illustrated by the graphitic shales of Worcester, Mass.[a] Graphite occurs to some extent with the very hard anthracite coals, a part of the carbon having passed over to the graphitic condition. Such graphitic coals occur in the Rhode Island coal field.[b] The reaction producing graphite as a metamorphic mineral requires great pressure and takes place with decrease in volume. This mineral in the sedimentary rocks is therefore a product of the zone of anamorphism.

Graphite is said to occur as an original constituent in some basaltic rocks. During the alterations of carbonaceous rocks the hydrocarbon compounds, as gases, oils, and bitumen, wander widely in the solutions. In some cases such compounds are deposited in the openings of original rocks. Later these compounds may be altered to graphite, and yet the carbon not be an original constituent of the magma from which the rocks crystallized.

Alterations.—Alterations of graphite are not recorded, but it is by no means certain that this mineral is not very slowly oxidized under favorable conditions in the belt of weathering.

THE SULPHIDES.

The sulphides which are important as rock-making minerals are pyrrhotite, pyrite, and marcasite. Many other sulphides are important in

[a] Perry, J. H., Note on a fossil coal plant found at the graphite deposit in mica-schists at Worcester, Mass.: Am. Jour. Sci., 3d ser., vol. 29, 1885, pp. 157–158.

[b] Shaler, N. S., Woodworth, J. B., and Foerste, A. F., Geology of the Narragansett Basin: Mon. U. S. Geol. Survey, vol. 33, 1899, p. 82.

the genesis of ore deposits. These, however, will be considered only in the chapter on that subject.

PYRRHOTITE, PYRITE, AND MARCASITE.

Pyrrhotite:
Fe_5S_6 to $Fe_{15}S_{16}$; chiefly $Fe_{11}S_{12}$.
Hexagonal.
Sp. gr. 4.58–4.64.

Pyrite:
FeS_2.
Isometric.
Sp. gr. 4.95–5.10.

Marcasite:
FeS_2.
Orthorhombic.
Sp. gr. 4.85–4.90.

Occurrence.—Pyrrhotite, pyrite, and marcasite are very widespread accessory minerals, occurring in rocks of all ages and all kinds. So far as known, these minerals are not abundant original pyrogenic constituents, although they frequently are found along the contact between intrusive and other rocks, occurring in both the intrusive and the intruded rocks. Pyrrhotite is an original mineral in meteorites. These minerals extensively form in rocks in volcanic districts through the action of solutions of hydrogen sulphide and other sulphide solutions upon iron salts. As secondary minerals in the sedimentary rocks, and to a less extent in the igneous rocks, the sulphides are extensively formed through the reducing action of organic compounds upon the sulphites and sulphates, especially the latter, and particularly iron sulphate. Such reduction is characteristic of the belt of cementation and the zone of anamorphism; but in the latter zone pyrrhotite or pyrite, rather than marcasite, probably forms.

The reducing agent of the sulphites and sulphates may be either a solid organic compound or one of its gaseous products of decomposition, such as carbon monoxide (CO) and carburetted hydrogen (CH_4). If the reducing agent be taken as CO, the reaction for pyrite and marcasite may be:

$$2FeSO_4+7CO=FeS_2+FeCO_3+6CO_2+k$$[a]

and for pyrrhotite:

$$12FeSO_4+45CO=Fe_{11}S_{12}+FeCO_3+45CO_2+k.$$

If the reducing agent were taken as carbon, similar results would be obtained, except that the amount of CO_2 would be less. This action, while

[a] See page 210.

ordinarily called a reduction, is reduction so far as the iron sulphate is concerned, but is oxidation so far as the carbon compound is concerned, and hence the explanation of the liberation of heat.

Pyrite, marcasite, and pyrrhotite are also doubtless produced by the action of soluble sulphides upon the iron oxides or iron salts. In the change from crystallized Fe_2O_3 (hematite) to FeS_2 (in the form of pyrite), the volume increases 56.14 per cent.

Alterstions.—The first alteration to be considered is that of marcasite into pyrite. In this alteration there is recrystallization, an increase of symmetry, a decrease of 2.98 per cent in volume, but no change in chemical composition. The heat effect is undetermined, but probably heat is liberated.

The mineral pyrrhotite by recrystallization passes into pyrite. This change may occur in volcanic districts by the action of hydrogen sulphide upon the pyrrhotite, the reaction perhaps being:

$$Fe_{11}S_{12}+10H_2S=11FeS_2+10H_2.$$

In this change the volume is increased 21.13 per cent.

The minerals pyrite and marcasite may by oxidation pass directly into (1) hydrated sesquioxide of iron, of which, ordinarily, limonite (not crystallized; sp. gr. 3.80) is the most common kind; (2) magnetite (isometric; sp. gr. 5.174); (3) ferrous sulphate, which may be removed in solution, or (4) may be decomposed by further oxidation, either at the place of formation or elsewhere, after a longer or shorter time, into hydrated sesquioxide of iron, ordinarily limonite. The reactions for marcasite and pyrite may be as follows, assuming in each case that the sulphur, or a part of it, is also oxidized:

(1) $4FeS_2+22O+3H_2O=2Fe_2O_3.3H_2O+8SO_2+k.$

(2) $3FeS_2+16O=Fe_3O_4+6SO_2+k$, or
$3FeS_2+4H_2O+4O=Fe_3O_4+4H_2S+2SO_2+k.$

(3) $FeS_2+6O=FeSO_4+SO_2+k$, or
$FeS_2+3O+H_2O=FeSO_4+H_2S+k.$

(4) $4FeSO_4+2O+7H_2O=2Fe_2O_3.3H_2O+4H_2SO_4+k.$

As shown in Chapter XI, on "Ore deposits," pyrite and marcasite also alter to hematite without oxidation by the reaction of an alkaline carbonate.

The alteration of common pyrrhotite into magnetite and limonite may be written as follows:

(5) $3Fe_{11}S_{12}+116O=11Fe_3O_4+36SO_2+k$, or
$3Fe_{11}S_{12}+36H_2O+8O=11Fe_3O_4+36H_2S+k.$

(6) $4Fe_{11}S_{12}+33H_2O+162O=11(2Fe_2O_3.3H_2O)+48SO_2+k.$

If in the production of the limonite the pyrrhotite passes through the stage of ferrous sulphate the reaction producing the sulphate may be:

(7) $Fe_{11}S_{12}+46O=11FeSO_4+SO_2+k$, or
$Fe_{11}S_{12}+H_2O+43O=11FeSO_4+H_2S+k$.

The change from the ferrous sulphate to the limonite is the same as in the case of pyrite and marcasite. Where water is present the SO_2 produced in the above reactions would unite with water and form H_2SO_3, or if further oxidized H_2SO_4.

As the end results of alteration are usually limonite or magnetite, the volume relations for these two compounds will be given. In the change of pyrite to limonite the volume is increased 2.93 per cent; to magnetite, is decreased 37.48 per cent. In the change from marcasite to limonite the volume is decreased 0.14 per cent; to magnetite, is decreased 39.34 per per cent. In the change of pyrrhotite to magnetite the volume is decreased 24.27 per cent; to limonite, is increased 24.68 per cent.

When pyrite and marcasite pass into limonite there is a change from a crystalline to an amorphous form. In the alteration of pyrite to magnetite the system does not change. In the alterations of pyrrhotite and marcasite to pyrite there are changes from lower degrees of symmetry to the highest degree of symmetry, that of the isometric system. The change from marcasite to pyrite occurs especially in the zone of anamorphism, subject to the principle there obtaining that the changes take place with decrease in volume. The change of marcasite to pyrite is an excellent illustration of the principle that where the pressure is great minerals tend to pass into other minerals having a higher degree of symmetry and a higher specific gravity (see pp. 360–365). The abundance of marcasite as an autogenic constituent in rocks not deeply buried, its absence in the rocks which have been in the lower zone, and the presence of pyrite in these rocks, are thus all explained. Where the pressure is small near the surface marcasite with lower symmetry and lower specific gravity than pyrite may abundantly form. At depth where the pressure is great pyrite of higher specific gravity and higher symmetry forms. If rocks near the surface in which marcasite has formed are buried to a great depth by superimposed strata the marcasite previously formed changes to pyrite.

Similar statements can not be made concerning pyrrhotite and pyrite, for these minerals have unlike compositions. Doubtless where the necessary

chemical reactions can take place there is a tendency in the lower zone for pyrrhotite to alter to pyrite.

The natural conditions for the transformation of pyrite, marcasite, and pyrrhotite to limonite are those of abundance of oxygen and moisture. These conditions are found in the zone of katamorphism, and especially in the belt of weathering. In this belt the process goes on with such rapidity that pyrite, marcasite, and pyrrhotite have generally been completely oxidized where the rocks have been long exposed to the reactions of the belt. The reactions are oxidation and hydration. They take place with great liberation of heat and, for pyrite and pyrrhotite, with some expansion of volume, and these changes may therefore be taken as typical illustrations of alterations of the belt of weathering.

The conditions for the formation of magnetite from pyrite, marcasite, and pyrrhotite are the presence of some oxygen, but not a sufficient amount to fully oxidize the iron, and considerable pressure. Where iron carbonate is present, which also alters to magnetite, oxygen is not necessary. This reaction is of great consequence. (See p. 244.) The alterations of the sulphides to magnetite involve a decrease of volume of 24 to 39 per cent and liberation of heat. Corresponding with this fact, the changes take place in the belt of cementation or in the zone of anamorphism.

THE FLUORIDES.

Among the fluorides the only important rock-making mineral is fluorite.

FLUORITE.

Fluorite:
CaF_2.
Isometric.
Sp. gr. 3.01–3.25.

Occurrence.—Fluorite occurs as an accessory constituent, especially in granitic and syenitic rocks. It is also found in other eruptive rocks, and in metamorphic rocks, such as the schists and marbles. It therefore has a somewhat widespread occurrence, but is of very subordinate importance.

Alterations.—By the action of alkaline waters fluorite alters into calcite (rhombohedral; sp. gr. 2.7135). Supposing the alkaline compound to be sodium carbonate, the reaction is:

$$CaF_2 + Na_2CO_3 = CaCO_3 + 2NaF + k.$$

The increase in volume of the calcite as compared with the fluorite is 47.66 per cent.

THE OXIDES.

The more important oxides occurring as rock-building constituents are those of silicon, iron, and titanium. The oxides of silicon are quartz, tridymite, and opal. The important oxides of iron are hematite, magnetite, and limonite. The important oxides of titanium are rutile, octahedrite, and brookite. One oxide of iron and titanium, or else a ferrous titanate, has a widespread occurrence; this is ilmenite.

QUARTZ.

Quartz:
SiO_2.
Rhombohedral.
Sp. gr. 2.653–2.654.

Occurrence.—Quartz is second in abundance only to the minerals of the feldspar group. According to Clarke,[a] quartz comprises 12 per cent of the lithosphere. It is very abundant as an original pyrogenic constituent of the igneous rocks, as an allogenic constituent of the clastic rocks, and as an autogenic mineral in all classes of metamorphosed rocks. The material for secondary quartz may be derived from the alterations of many minerals in situ, or from the decomposition of minerals at some distance. The most widespread of all the alterations which furnish silica to the solutions is that of the decomposition of the silicates by carbonic acid in the belt of weathering, with the simultaneous production of carbonates and quartz, or a solution of colloidal silicic acid from which opal, chert, or quartz may later separate. Such quartz may be extensively deposited from the solutions in the porous rocks of the belt of cementation. It there fills the minute spaces between the individual grains of sedimentary rocks. It occupies spaces in porous tuffs or in vesicular igneous rocks. It fills openings between laminæ, and joint, fault, and breccia openings. The quantity of quartz thus deposited is far greater than that of any other mineral, and not improbably greater than that of all other minerals combined. By this process the rocks are cemented. (See pp. 617–621.) Not only may the openings be occupied by quartz, but at the time of the deposition of the quartz other minerals may dissolve and their places be taken by the quartz. This process of deposition of silica as quartz is called silicification. (See p. 205.)

[a] Clarke, F. W., Analyses of rocks from the laboratory of the United States Geological Survey, 1880–1899: Bull. U. S. Geol. Survey No. 168, 1900, p. 16.

As a metamorphic mineral, quartz is derived from actinolite, anorthite, anorthoclase, anthophyllite, augite, biotite, bronzite, chalcedony, cummingtonite, diopside, enstatite, epidote, garnet, grossularite, hornblende, hypersthene, microcline, olivine, opal, orthoclase, plagioclase, prehnite, pyrope, sahlite, scapolites, serpentine, tridymite, and zoisite.

Modifications.—The most frequent and important modification of quartz is by recrystallization. Crystallized quartz is dissolved under conditions of weathering, as are all other minerals. This process is, however, exceedingly slow. As a result of solution the quartz crystals may be corroded. Such corrosion has been described by Hayes.[a] In the belt of cementation, and especially adjacent to trunk channels of circulation, quartz may be extensively dissolved from veins and from the wall rocks. (See pp. 848–849.)

Granulation and recrystallization of quartz occur on a most extensive scale in all quartzose rocks which are subjected to mass-mechanical action or other favorable conditions in the zone of anamorphism. These changes involve no heat and volume reactions so far as the quartz itself is concerned, except that as the original minerals may be strained, or the new grains are imperfectly adjusted, the change may involve a slight expansion. But such expansion is followed by an equal contraction when the material is recrystallized into quartz free from strain. In the recrystallization many small individuals may be merged into one large individual. In some instances of recrystallization, where large grains are produced from smaller ones, the large individuals may average more than a million times as great as the small individuals from which they are derived. (See p. 695.) In the production of a comparatively few large individuals from a multitude of small individuals there is probably a release of energy. (See p. 771.) During recrystallization the material taken into solution may be deposited practically in situ or may travel far and be extensively deposited elsewhere. Often quartz deposited in situ, or nearly so, can not be discriminated from quartz deposited from solutions coming from distant sources, as above described.

A second modification of quartz only less important than that of recrystallization is silication by the union with bases united with other acids, thus forming silicates. Of such acids carbonic is by far of

[a] Hayes, C. W., Solution of silica under atmospheric conditions: Bull. Geol. Soc. America, vol. 8, 1897, pp. 213–220.

the greatest consequence. Some of the more common minerals in which silication occurs on an extensive scale are calcite, dolomite, ankerite, and siderite, thus producing wollastonite, diopside, tremolite, sahlite, actinolite, and grünerite. The silica may unite with the bases of various carbonates producing various complex silicates, such as chondrodite, augite, hornblende, garnet, etc. At the same time the material of previous silicates may be absorbed. The heat and volume reactions in many of these changes may be found under the carbonates mentioned.

In this process of silication of carbonates it is not often possible to identify the remnants of the quartz individuals which furnished the silica for the reactions. But apparently the quartz particles which furnished the silica for the process of silication may be identified in some instances. This is best seen for such fibrous minerals as serpentine, talc, and actinolite, the needles or fibers of which appear to grow into the quartz, in some instances deeply. In such cases it seems clear that the silica of the quartz furnished at least a part of the silica for the silicate, the bases being furnished by the solutions.

One of the best instances of the extensive union of quartz with bases, producing serpentine pseudomorphous after quartz, is that described by Becker.[a] He describes the exteriors of original clastic grains of quartz to be "entirely occupied by felted fibers of serpentine, and long, slender microlites pierce the quartz grain toward its center, like pins in a cushion."[b] This is but one illustration of a very widespread replacement of quartz by serpentine in the Coast Ranges. The growth of actinolite into quartz is illustrated in the Tyler slate of the Penokee district of Wisconsin."[c]

In instances where the quartz furnishes the silica for the penetrating silicates the migration of the silica is microscopical, and it might be supposed that the reactions occur without the solution of the silica of the quartz; but it seems probable, even in such cases as these, that there is solution of the silica before combination with the bases. In such reactions it is presumed that the bases which unite with the silica were before united with some other acid, and it is only when the previous combination is known that the heat and volume relations of the reactions can be ascertained.

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[a] Becker, G. F., Geology of the quicksilver deposits of the Pacific slope: Mon. U. S. Geol. Survey, vol. 13, 1888, pp. 120–127.

[b] Becker, cit., p. 124.

[c] Irving, R. D., and Van Hise, C. R., The Penokee iron-bearing series of Michigan and Wisconsin: Mon. U. S. Geol. Survey, vol. 19, 1892, pp. 210–215.

In a third class of changes quartz may be wholly replaced by other minerals, as by magnetite and hematite. Very frequently the deposition of the new minerals seems to be conditioned upon the solution of the quartz. The replacement of quartz by iron oxide is illustrated in the Lake Superior region in both the iron-bearing and the slate formations.[a]

The most favorable conditions for the solution of silica, especially of that formed by the decomposition of the silicates by carbonation, are furnished by the belt of weathering. The most favorable conditions for the deposition of silica as quartz are those of the belt of cementation. The solution of silica in the belt of weathering of the zone of katamorphism and its deposition in the belt of cementation of this zone is perhaps the best illustration of the principle explained on pages 634–636, that material dissolved in the belt of weathering may be extensively deposited in the belt of cementation. Recrystallization of quartz mainly takes place in the zone of anamorphism, although it undoubtedly occurs to some extent in the zone of katamorphism, and especially in the belt of cementation. The process of silication takes place almost invariably with decrease in volume, provided all the compounds concerned are solids. Where the carbonates are silicated the decrease in volume ranges from 20 to 40 per cent. Silication occurs upon a great scale in the zone of anamorphism—is, indeed, one of the most distinctive chemical reactions of that zone.

TRIDYMITE.

Tridymite:
SiO_2
Hexagonal, or pseudo-hexagonal.
Sp. gr. 2.28–2.33.

Occurrence.—Tridymite usually occurs as an autogenic mineral in cavities in lavas, such as rhyolite, andesite, trachyte, etc.

Modifications.—Tridymite is dissolved more readily than quartz. The material of tridymite may go through any of the changes which silica of quartz may pass through, with the difference that its recrystallization would result in the production of quartz (rhombohedral; sp. gr. 2.652–2.654) rather than the original mineral, tridymite. The changes of tridymite into other minerals than quartz need not be discussed in detail, since the reactions are the same as with quartz, except that the volume decrease is greater

[a] Van Hise, C. R., and Bayley, W. S., The Marquette iron-bearing district of Michigan: Mon. U. S. Geol. Survey, vol. 28, 1897, pp. 370, 400–405.

in the changes of tridymite than with quartz. In the change of tridymite to quartz there is a diminution of volume, amounting to 14.24 per cent, and there is also probably liberation of heat. Energy is therefore potentialized in tridymite as compared with quartz. The change is one which is particularly likely to occur in the zone of anamorphism, where pressure is the dominant factor. In the fact that quartz is a denser mineral than tridymite we probably have a reason not only for the passage of tridymite into quartz in the lower zone, but for the absence of tridymite as an original pyrogenic constituent in the plutonic igneous rocks which crystallized originally in this zone. Under its conditions the denser mineral, quartz, formed.

OPAL.

Opal:
$SiO_2.nH_2O$ (H_2O 2 to 13 per cent; but mostly 3 to 9 per cent.)
Amorphous.
Sp. gr. 2.1–2.2.

Occurrence.—Opal, like most other hydrous minerals, is a product of the zone of katamorphism. Opal is a direct deposit from hot springs. In the sedimentary rocks it is abundantly formed from the siliceous skeletons of certain animals and plants, such as radiolaria, sponges, and diatoms. Opal is plentifully deposited in cavities in rocks by subterranean waters. Its most common places of occurrence are the limestones, where it is largely of organic origin, and the porous igneous rocks, especially as amygdules of the amygdaloids, where it is a chemical precipitate.

In general, as a metamorphic product opal may be derived from the same minerals as quartz.

Modifications.—The most frequent change of opal is to quartz (rhombohedral; sp. gr. 2.652–2.654). Frequent intermediate products are chalcedony and chert, which appear to be partly crystalline substances. (See p. 222.) In the passage of opal into quartz, the changes are three: dehydration, reduction of volume, and recrystallization. Supposing the composition of the opal is $SiO_2.\frac{1}{6}H_2O$, which would be about 6 per cent of water, the decrease of volume would be 22.81 per cent. The change from opal to quartz above given is commonly accomplished by solution and redeposition or recrystallization. When the material is taken into solution this silica may be deposited near by or transported elsewhere. It may unite with free bases, producing silicates; it may displace other acids combined with bases,

as, for instance, carbonic acid, thus also producing silicates. The heat and volume relations of these reactions are discussed under "Quartz."

The reactions of dehydration, crystallization, and lessening of volume, as seen on pages 167–170, are particularly characteristic of the zone of anamorphism, and it is in this zone that the change from opal to quartz probably most extensively occurs. As evidence of this is the frequent occurrence of opal in the zone of katamorphism, and the general absence of opal in the rocks which have been metamorphosed in the lower zone.

CHERT, CHALCEDONY, ETC.

Standing between opal and quartz are numerous varieties of partly crystallized or very finely crystallized silica, of which chert and chalcedony may be taken as the more important kinds. With these substances are frequently small but variable amounts of opal containing combined water. The specific gravities of chert and chalcedony are intermediate between those of opal and quartz, i. e., between 2.15 and 2.65. Their most frequent occurrence is as veins, nodules, belts, and members in carbonate formations. Ordinarily they are derived from organic forms, such as radiolaria, diatoms, and sponges, which lived under conditions similar to those under which the limestone-building animals lived. (See p. 817.)

Chert and chalcedony are derived from opal. The material here included varies from that which is close to opal, having only a few minute crystallized spots, through material which shows more and more evidence of crystallization, to material which contains comparatively little amorphous silica, and thence into fully crystallized silica or quartz. The transition varieties may have the peculiar spotty appearance in polarized light characteristic of ordinary chert or the peculiar radial fibrous polarization of chalcedony or any combination of the two.

The alterations of chert and chalcedony are into quartz, or by combination with bases producing silicates, the same as opal. The chemistry and physics of the change are the same as for opal except that the decrease in volume is less, and therefore they need not be repeated.

HEMATITE GROUP.

CORUNDUM, HEMATITE, AND ILMENITE.

Corundum:
Al_2O_3.
Rhombohedral.
Sp. gr. 3 95–4.10.
Hematite:
Fe_2O_3.
Rhombohedral.
Sp. gr. 5.20–5.25.
Ilmenite:
$FeTiO_3$; varies to $mFeTiO_3 . nFe_2O_3$.
Rhombohedral.
Sp. gr. 4.50–5.02.

CORUNDUM.

Occurrence.—In Canada at one locality corundum occurs as an original constituent of a syenite.[a] Also, corundum as an accessory mineral has been noted in granite, andesite, and other rocks. Corundum is, therefore, an original pyrogenic constituent of igneous rocks. Corundum occurs along the contact of intrusive basic rocks rich in alumina, especially those containing more than 30 per cent, such as peridotites and pyroxenites. The intruded rocks may be either igneous rocks or gneisses and schists. But where corundum occurs in veins along contacts it is in many cases an aqueo-igneous product (see pp. 720–728) or an aqueous deposit. Corundum is a widespread accessory constituent in various micaceous, chloritic, and hornblendic schists and gneisses, and in marble. Corundum, as a metamorphic mineral, is associated with chlorite and corundophilite. It is often associated with other heavy metamorphic minerals, such as andalusite, sillimanite, cyanite, spinel, rutile, etc. As a metamorphic mineral it is derived from andalusite, cyanite, diaspore, gibbsite, sillimanite, staurolite, and topaz.

Alterations.—Corundum alters into diaspore (orthorhombic; sp. gr. 3.40), gibbsite (monoclinic; sp. gr. 2.35), spinel (isometric; sp. gr. 3 8), sillimanite (orthorhombic; sp. gr. 3.235), cyanite (triclinic; sp. gr. 3.615), muscovite (damourite), (monoclinic; sp. gr. 2.88), margarite (monoclinic; sp. gr. 3.035), and zoisite (orthorhombic; sp. gr. 3.31). The reactions for the formation of diaspore and gibbsite are simple reactions of hydration. The reactions for

[a] Miller, W. G., Economic geology of eastern Ontario; corundum and other minerals: Seventh Rept. Ontario Bureau of Mines, 1897, Toronto, 1898, p. 213.

the production of the other minerals require the addition of various other constituents—in the case of spinel, magnesia; in the case of sillimanite and cyanite, silica; in the case of the complicated silicates, muscovite, margarite, and zoisite, various bases and a large amount of silica. Therefore in these cases it is clear that the common statement that corundum alters to the minerals muscovite, margarite, and zoisite can have only the meaning that the relations are such that corundum furnishes the alumina for the resultant compound, and that the additional compounds are derived from another source. It will be assumed in the alterations that the magnesia, lime, and potash are derived from the solid carbonates and that the silica is added as quartz. The equations for the reactions are as follows:

(1) $Al_2O_3+H_2O=2[AlO.(OH)]+k.$
(2) $Al_2O_3+3H_2O=2Al(OH)_3+k.$
(3) $Al_2O_3+MgCO_3=MgAl_2O_4+CO_2+k.$
(4) $Al_2O_3+SiO_2=Al_2SiO_5+k.$
(5) $3Al_2O_3+6SiO_2+K_2CO_3+2H_2O=2H_2KAl_3Si_3O_{12}+CO_2+k.$
(6) $2Al_2O_3+2SiO_2+CaCO_3+H_2O=H_2CaAl_4Si_2O_{12}+CO_2+k.$
(7) $3Al_2O_3+6SiO_2+4CaCO_3+H_2O=H_2Ca_4Al_6Si_6O_{26}+4CO_2+k.$

The increase in volume as compared with corundum is, for diaspore (equation 1), 39.25 per cent; for gibbsite (equation 2), 161.83 per cent. The volume of the corundum and the magnesite in passing to the spinel (equation 3) is decreased 29.17 per cent. The volume of the corundum and quartz in passing into sillimanite (equation 4) is increased 4.38 per cent; into cyanite (equation 4) is decreased 6.59 per cent. If the volume of the corundum be compared with that of the muscovite (equation 5), with that of the margarite (equation 6), and with that of the zoisite (equation 7), there will be great volume increases. If, on the other hand, all the products which unite with the corundum in each case, with the exception of the water, be counted as solid, there would be small increase in the volume for muscovite, a considerable decrease for zoisite, and a small decrease for margarite. On the first hypothesis the increase in the volume in the production of muscovite is 264.25 per cent; in margarite, 159.02 per cent; in zoisite, 261.34 per cent. On the second hypothesis the increase in volume in the production of muscovite is 1.62 per cent; to form margarite the decrease is 1.22 per cent; to form zoisite the decrease is 23.58 per cent.

It is reasonably certain that the passage of corundum to diaspore and gibbsite is a reaction characteristic of the zone of katamorphism, and

especially the belt of weathering. It is almost equally certain that the passage of corundum into spinel, sillimanite, and cyanite is characteristic of the zone of anamorphism.

The case, however, is not clear in reference to the muscovite, margarite, and zoisite. The equations as written are those of silicifiation and slight hydration. If these equations be correct, they should occur in the lower part of the belt of cementation or in the zone of anamorphism. It is tolerably certain that margarite, zoisite, and muscovite form in the lower part of the belt of cementation; but the zone in which muscovite characteristically develops is that of anamorphism. It is not at all impossible that the potassium carbonate, and perhaps the calcium carbonate, or even the silica, are added in solution for the margarite and zoisite. In this case there would be a considerable volume increase. Whether the same may be assumed for the muscovite is uncertain. Very likely the materials added to the corundum are in some cases carried in by the solutions, in others are derived from adjacent minerals, and in still others partly from both. Where the lime and potash are derived from minerals adjacent, they may come from other compounds than carbonates, and the silica may have been previously united with other bases. So far as this is so, in considering the variations in volume the minerals from which the elements added to the corundum to produce the muscovite, margarite, and zoisite were derived must be taken into account. It is clearly impracticable in the present state of knowledge to give definite statements as to the volume changes for these minerals.

HEMATITE.

Occurrence.—Hematite is a pyrogenic constituent in igneous rocks and is an abundant metamorphic mineral. Its most abundant source in the metamorphic rocks is by the dehydration of limonite, a reaction occurring with the absorption of heat and reduction of volume. A second important source of hematite is from iron carbonate by loss of carbon dioxide and by oxidation, a reaction occurring with the liberation of heat and reduction of volume. Hematite may also be produced by the oxidation of magnetite, a reaction resulting in liberation of heat and expansion of volume. Frequently after this change the hematite has the isometric form of the original magnetite and is called martite. A fourth source of hematite is by the oxidation of the ferrous iron of silicates at the time of their decomposition.

A fifth source is by oxidation of ferrous iron solutions, which may result in the precipitation of hematite. The first reaction occurs most extensively in the zone of anamorphism; the other four occur in the zone of katamorphism, and to these positions the heat and volume reactions correspond. Finally, as shown in Chapter XII, on "Ore deposits," hematite may be formed from pyrite by the action of alkaline carbonate solutions.

In summary, hematite is derived from actinolite, ankerite, anthophyllite, biotite, bronzite, garnet, greenalite, grünerite, hornblende, hypersthene, ilmenite, limonite, magnetite, olivine, parankerite, pyrite, serpentine, and siderite.

Alterations.—The most frequent alteration of hematite is into limonite (amorphous; sp. gr. 3.6–4). The reaction is as follows:

$$2Fe_2O_3+3H_2O=2Fe_2O_3.3H_2O+k.$$

In the change the volume is increased 60.72 per cent. A second alteration of hematite is into magnetite (isometric; sp. gr. 5.168–5.18). This may be accomplished by any of the reducing agents furnished by organic compounds. Supposing the reducing agent to be the partially oxidized carbon compound CO, the reaction is:

$$3Fe_2O_3+CO=2Fe_3O_4+CO_2+k.$$

While a reduction of the oxide of iron occurs a simultaneous oxidation of the organic compound occurs, and the end result is the liberation of heat. In the change the volume is decreased 2.38 per cent. A third alteration of hematite is to pyrite (isometric; sp. gr. 5.025) or marcasite (orthorhombic; sp. gr. 4.875). In the best-known instances siderite (rhombohedral; sp. gr. 3.855) or some other iron-bearing carbonate is simultaneously produced. The reaction may be:

$$Fe_2O_3+2H_2S+CO_2=FeS_2+FeCO_3+2H_2O+k.$$

In the change to pyrite and siderite the volume is increased 76.12 per cent, and to marcasite and siderite 78.73 per cent.

The alterations of hematite to limonite occur in the zone of katamorphism, and especially in the belt of weathering. Corresponding with this position the reaction is with liberation of heat and expansion of volume. The alteration of hematite into magnetite occurs in the belt of cementation and the zone of anamorphism. This agrees with the fact that the reaction

liberates heat and diminishes the volume. The alteration of hematite to pyrite and marcasite is best known where organic compounds are present to reduce sulphuric acid to hydrosulphuric acid and to furnish carbonic acid to form the carbonates. The reaction is especially characteristic of the belt of cementation, and to this position the expansion of volume and the liberation of heat correspond.

ILMENITE.

Occurrence.—Ilmenite is an abundant pyrogenic constituent of the igneous rocks. It is found both as an allogenic and as an autogenic constituent in metamorphic rocks. As an autogenic constituent the compounds which unite to produce it have not been worked out. As a metamorphic mineral ilmenite is derived from perovskite and rutile.

Alterations.—Ilmenite alters to titanite (monoclinic; sp. gr. 3.48), to rutile (tetragonal; sp. gr. 4.18–4.25), and to octahedrite, or anatase (tetragonal; sp. gr. 3.82–3.95). With these minerals magnetite (isometric; sp. gr. 5.174) or hematite (rhombohedral; sp. gr. 5.225) or limonite (amorphous; sp. gr. 3.80) is simultaneously produced. One of the most frequent reactions in the production of titanite is probably along the following lines:

$$3FeTiO_3+3CaCO_3+3SiO_2+O=3CaTiSiO_5+Fe_3O_4+3CO_2+k.$$

The decrease in volume of the ilmenite, calcite, and quartz in passing into titanite and magnetite, supposing the CO_2 to escape, is 22.35 per cent; but the increase in volume of the titanite as compared with the ilmenite alone is 76.35 per cent. The alteration of ilmenite to rutile and octahedrite, with combined magnetite, is as follows:

$$3FeTiO_3+O=3TiO_2+Fe_3O_4+k.$$

In case hematite is produced instead of magnetite the reaction is:

$$2FeTiO_3+O=2TiO_2+Fe_2O_3+k.$$

In case limonite is produced, one and one-half molecules of water are added to both sides of the equation.

The increase in volume of the ilmenite in passing into rutile and magnetite is 6.02 per cent; into octahedrite and magnetite, 11.07 per cent. In case hematite or limonite be produced, the increase in volume is correspondingly greater.

It is certain that titanite forms from ilmenite in the lower zone. In this zone, as explained on pp. 764–765, the $CaCO_3$ and SiO_2 can not be supposed

to have been brought in from the outside, and therefore the change takes place with decrease in volume. It is also certain that titanite forms extensively in connection with chlorite, which commonly develops in the belt of cementation. In this case the calcium carbonate and silica may be introduced in solution from an outside source, under which circumstances the volume is increased.

The alterations of ilmenite to rutile and octahedrite, or any combination of them, certainly occur in the zone of katamorphism, and to this position the heat and volume reactions correspond. However, I have not found sufficient information on the subject to assert that these reactions do not also occur in the zone of anamorphism.

SPINEL GROUP.

SPINEL, MAGNETITE, AND CHROMITE.

Spinel:
$MgAl_2O_4$.
(Hercynite, $FeAl_2O_4$.)
(Pleonaste, $[MgFe]\,[AlFe]_2O_4$.)
(Picotite, $[MgFe]\,[AlCr]_2O_4$.)
Isometric.
Sp. gr. 3.5–4.1.

Magnetite:
Fe_3O_4.
Isometric.
Sp. gr. 5.168–5.180.

Chromite:
$FeCr_2O_4$.
Isometric.
Sp. gr. 4.32–4.57.

SPINEL.

Occurrence.—Spinel occurs as an original constituent in the igneous rocks, but is much more abundantly present as a secondary constituent in the metamorphic rocks, especially those which are rich in magnesium. In many cases it is secondary to olivine and other minerals rich in magnesium. The more important minerals from which spinel is derived are almandite, biotite, chlorite, corundum, diaspore, garnet, gibbsite, olivine, and pyrope.

Alterations.—According to Dana, spinel has been observed as altering to talc (orthorhombic or monoclinic; sp. gr. 2.75), serpentine (monoclinic; sp. gr. 2.575), and mica (monoclinic; sp. gr. 2.88–2.90). However, the character of the alterations and the conditions under which they occur are so little known that I shall not attempt to treat them from the physical-chemical point of view.

MAGNETITE.

Occurrence.—Magnetite is a very abundant pyrogenic constituent in igneous rocks. It is abundantly deposited from solutions, and especially from solutions bearing iron carbonate, according to the reaction:

$$3FeCO_3+O=Fe_3O_4+3CO_2+k.$$

Magnetite also extensively forms from siderite in situ. These changes liberate heat and decrease the volume. A third source of magnetite is by incomplete oxidation of pyrite and marcasite, reactions occurring with liberation of heat and diminution of volume. Fourth, frequently siderite and iron sulphide together pass into magnetite with decrease in volume. (See pp. 244, 845.) A fifth way in which magnetite may be produced is by the reduction of hematite by organic compounds, a reaction occurring with the liberation of heat, because of the simultaneous oxidation of the organic compounds, and with diminution of volume. A sixth way in which magnetite is produced is by the incomplete oxidation of ferrous iron of silicates; for instance, olivine and garnet.

In summary, magnetite is derived from actinolite, ankerite, arfvedsonite, augite, biotite, bronzite, diopside, garnet, greenalite, grünerite, hematite, hornblende, hypersthene, ilmenite, marcasite, and pyrite.

Alterations.—Magnetite alters into hematite (rhombohedral; sp. gr. 5.225), limonite (amorphous; sp. gr. 3.80), and siderite (rhombohedral; sp. gr. 3.83–3.88). The reactions are as follows:

(1) $2Fe_3O_4+O=3Fe_2O_3+k.$
(2) $4Fe_3O_4+2O+9H_2O=3(2Fe_2O_3.3H_2O)+k.$
(3) $Fe_3O_4+CO+2CO_2=3FeCO_3+k.$

In the change the increase in volume is, for (1), 2.44 per cent; for (2), 64.63 per cent, and for (3), 101.30 per cent. The increase in volume in the change from magnetite to siderite—over 100 per cent—is the greatest volume change in which only two minerals are concerned which the calculations of Mr. Lincoln have given, with the exception of the alteration of corundum into gibbsite. (See p. 224.) All of the above changes are well known to occur in the zone of katamorphism, and corresponding with this position they all take place with the liberation of heat, expansion of volume, and decrease in symmetry.

CHROMITE.

Occurrence.—Chromite occurs in the igneous rocks, especially those rich in magnesium. It also occurs in the metamorphic rocks, often in connec-

tion with serpentine. In these positions it is very frequently a secondary product of olivine. The reactions occurring in its production are given under that mineral.

Alterations.—The alteration of chromite into other minerals has not been noted.

RUTILE GROUP.

RUTILE, OCTAHEDRITE, AND BROOKITE.

Rutile:
TiO_2.
Tetragonal.
Sp. gr. 4.18–4.25.
Octahedrite:
TiO_2.
Tetragonal.
Sp. gr. 3.82–3.95.
Brookite:
TiO_2.
Orthorhombic.
Sp. gr. 3.87–4.082.

Occurrence.—Rutile is a pyrogenic constituent in igneous rocks, and has a widespread occurrence in the clastic and metamorphic rocks, both as an allogenic and as an autogenic constituent, in the latter case generally being derived from ilmenite. Rutile is also derived from brookite, ilmenite, octahedrite, and titanite.

Octahedrite in the metamorphic rocks is a secondary alteration of other titanium-bearing minerals, especially of titanite. It is also derived from ilmenite.

Brookite occurs sparingly, both in altered igneous rocks and in sedimentary rocks. In some cases it is secondary to titanite.

Alterations.—Both octahedrite and brookite alter to rutile (tetragonal; sp. gr. 4.18–4.25). In the case of octahedrite the decrease in volume is 7.83 per cent; in the case of brookite the decrease is 5.69 per cent. The heat change is undetermined, but probably the alterations occur with the liberation of heat. If this be the case the alterations involve recrystallization, diminution of volume, and liberation of heat. In the case of octahedrite the symmetry remains the same; in the case of brookite the symmetry is increased.

It may be inferred that such changes as these occur in both zones, being in all respects analogous to the changes which take place in dolomitization. (See pp. 238–240.) However, the geological occurrences of these alterations have not been given with such definiteness as to enable one to make definite statements as to the actual facts.

In this connection the experiments of Hautefeuille[a] are very interesting. He produced rutile, brookite, and octahedrite from the same compounds, but at different temperatures, rutile forming when red heat was used, brookite when the temperature was between that required for the volatilization of cadmium and zinc, and octahedrite when the temperature was a little below that for the volatilization of cadmium. Rutile, the mineral with the highest specific gravity, forms at the highest temperature, and high temperature is especially characteristic of the zone of anamorphism.

Rutile may alter into ilmenite (rhombohedral; sp. gr. 4.75) and into titanite (monoclinic; sp. gr. 3.48). In the change to ilmenite the reactions may be:

(1) $TiO_2+Fe_3O_4=FeTiO_3+Fe_2O_3+k$, or
(2) $TiO_2+FeCO_3=FeTiO_3+CO_2+k$.

In (1) the decrease in volume of the ilmenite and hematite as compared with the rutile and magnetite is 1.88 per cent. In (2) the decrease in volume is 34.77 per cent, provided the iron carbonate is present as solid siderite and the CO_2 escapes.

In the change to titanite the most probable reaction is:

(3) $TiO_2+CaCO_3+SiO_2=CaTiSiO_5+CO_2+k$.

The decrease in volume is 28.17 per cent, provided the compounds which unite with the rutile are solids and the liberated CO_2 escapes.

Those who have described the changes of rutile to ilmenite and titanite have not indicated whether or not they occur as deep-seated alterations. It may, however, be anticipated that such is the case, for they are changes which involve liberation of heat and condensation of volume, and therefore the kind which normally occur in the zone of anamorphism.

DIASPORE GROUP.

DIASPORE AND LIMONITE.

Diaspore:
$AlO(OH)$.
Orthorhombic.
Sp. gr. 3.3–3.5.

Limonite:
$2Fe_2O_3.3H_2O$.
Amorphous.
Sp. gr. 3.6–4.00.

[a] Dana, J. D., A system of mineralogy; Descriptive mineralogy, by E. S. Dana; Wiley & Sons, New York, 6th ed., 1892, p. 239.

DIASPORE.

Occurrence.—Diaspore is especially found in the serpentine- or chlorite-bearing schists and gneisses and in dolomites. In these rocks it is frequently associated with corundum. Diaspore has been recorded as a constituent of granite, nepheline-syenite, and basaltic rocks. As noted on other pages, for the alterations of various minerals in the zone of katamorphism, especially the belt of weathering, it may be produced as one of the alteration products of the following minerals: Biotite, corundum, gibbsite, haüynite, muscovite, nephelite, noselite, phlogopite, scapolites, sodalite.

Alterations.—No alterations of diaspore are recorded. However, it is probable that where diaspore is deposited in sedimentary rocks and is deeply buried, so as to undergo alteration in the zone of anamorphism, it passes into corundum (rhombohedral, sp. gr. 4.025); or, like corundum, unites with other bases to produce such minerals as spinel (isometric, sp. gr. 3.8); sillimanite (orthorhombic, sp. gr. 3.235), and cyanite (triclinic, sp. gr. 3.615); muscovite (monoclinic, sp. gr. 2.88); margarite (monoclinic, sp. gr. 3.035); and zoisite (orthorhombic, sp. gr. 3 31). So far as the hydrous minerals muscovite, margarite, and zoisite are formed, the water may have been derived from the diaspore, which contains more water, and thus their formation be really a process of dehydration and silication. For these supposed reactions the equations may be:

(1) $2AlO(OH)=Al_2O_3+H_2O-k.$
(2) $2AlO(OH)+MgCO_3=MgAl_2O_4+CO_2+H_2O-k.$
(3) $2AlO(OH)+SiO_2=Al_2SiO_5+H_2O-k.$
(4) $6AlO(OH)+6SiO_2+K_2CO_3=2H_2KAl_3Si_3O_{12}+CO_2+H_2O-k.$
(5) $4AlO(OH)+2SiO_2+CaCO_3=H_2CaAl_4Si_2O_{12}+CO_2+H_2O-k.$
(6) $6AlO(OH)+6SiO_2+4CaCO_3=H_2Ca_4Al_6Si_6O_{26}+4CO_2+2H_2O-k.$

Supposing that all the compounds in the first member of the equation are solids, and that the liberated CO_2 and H_2O escape, the decrease in volume for corundum (1) would be 28.18 per cent; for spinel (2), 40.39 per cent; for sillimanite (3), 13.52 per cent; for cyanite (3), 22.61 per cent; for muscovite (4), 54.21 per cent; for margarite (5), 14.08 per cent; for zoisite (6), 29.44 per cent. All take place with absorption of heat. Therefore all of these reactions are characteristic of the zone of anamorphism.

LIMONITE.

Occurrence.—Limonite as a mineral is produced either as an original chemical precipitate or by the alteration of other minerals. It is not,

so far as known, an original pyrogenic constituent of the igneous rocks. The most important source of bodies of limonite is precipitation from iron-bearing solutions, especially iron carbonate. For iron carbonate the reaction is—

$$4FeCO_3+2O+3H_2O=2Fe_2O_3.3H_2O+4CO_2+k.$$

A second important source for limonite is the oxidation and hydration of solid iron carbonate in rocks, especially siderite, ankerite, parankerite, and iron-bearing limestone or dolomite. The source next in importance is the oxidation and hydration of pyrite, marcasite, and other sulphides. A fourth important source of limonite is the oxidation and hydration of the ferrous iron of silicates. A fifth source is the hydration of hematite. A sixth but unimportant source is the oxidation and hydration of magnetite. All the reactions involve oxidation or hydration, or both, and therefore take place with the liberation of heat. In the production of limonite from iron carbonate there is an important contraction of volume; in the other cases the volume of the limonite is greater than that of the compounds from which it is derived. All the above reactions producing limonite occur in the zone of katamorphism, and the controlling factor is the first part of van't Hoff's law, that of chemical reactions with the liberation of heat. Limonite does not develop in the zone of anamorphism.

In summary, limonite is derived from the following minerals: Actinolite, ankerite, anthophyllite, arfvedsonite, biotite, bronzite, epidote, garnet, grecalite, grünerite, hematite, hornblende, hypersthene, ilmenite, magnetite, marcasite, olivine, parankerite, pyrite, pyrrhotite, serpentine, and siderite.

Alterations.—The important alterations of limonite are into hematite (rhombohedral; sp. gr. 5.20–5.25) and siderite (rhombohedral; sp. gr. 3.83–3.88). Hematite produced from limonite may be earthy or crystalline. The reaction is—

$$2Fe_2O_3.3H_2O=2Fe_2O_3+3H_2O-k.$$

The decrease of volume is 37.78 per cent. The change is therefore one of dehydration, reduction of volume, and crystallization. The transformation takes place on a great scale in the zone of anamorphism, that in which pressure controls whether heat is absorbed or liberated.

The second important change of limonite is into iron carbonate. Where this change occurs organic compounds are commonly present and

decomposing to serve as reducing agents and to furnish abundant CO_2 to unite with the iron. The reduction may be by the passage of CO into CO_2, of C into CO_2, or of C into CO, as follows:

(1) $2Fe_2O_3.3H_2O+2CO+2CO_2=4FeCO_3+3H_2O+k.$
(2) $2Fe_2O_3.3H_2O+C+3CO_2=4FeCO_3+3H_2O+k.$
(3) $2Fe_2O_3.3H_2O+2C+4CO_2=4FeCO_3+3H_2O+2CO+k.$

So far as the iron is concerned, its reduction and dehydration absorb heat, but the oxidation of the C or CO and the union of the CO_2 and FeO both liberate heat, the amount of which is greater than that absorbed, so that in each of these reactions heat is liberated. In all of the reactions the volume is increased 22.27 per cent.

The reduction of the iron of limonite so as to produce protoxide for the formation of iron carbonate may of course be accomplished by carbureted hydrogen, especially methane (CH_4), rather than by the compounds suggested; but the carbureted hydrogen compounds are so numerous and the resultant compounds so uncertain that no attempt will be made to formulate equations for possible changes with these substances as reducing agents.

The change of limonite to siderite is one which occurs extensively in rocks bearing organic compounds in the zone of katamorphism. The formation of the abundant siderites which are used as iron ores of Carboniferous and later age are believed for the most part to be thus derived from limonite in the upper zone. The reactions correspond perfectly to this position, being those which occur with liberation of heat and very considerable expansion of volume. The siderite thus formed may later be decomposed into various other compounds, or even reproduce limonite, but the consideration of such changes belongs under "Siderite."

BRUCITE GROUP.

BRUCITE AND GIBBSITE.

Brucite:
$Mg(OH)_2$.
Rhombohedral.
Sp. gr. 2.38–2.40.

Gibbsite (hydrargillite):
$Al(OH)_3$.
Monoclinic.
Sp. gr. 2.28–2.42.

BRUCITE.

Occurrence.—Brucite is one of the minerals which is produced in the upper physical-chemical zone, especially in the belt of weathering. Brucite is produced by the alterations of minerals rich in magnesia, being recorded as secondary to chondrodite, clinohumite, humite, and serpentine. It is especially prevalent in serpentinous rocks and veins. Doubtless in many instances it forms simultaneously with the serpentine and perhaps other minerals, rather than secondary to them.

Alterations.—The one alteration of brucite noted is that of carbonation, into hydromagnesite (monoclinic; sp. gr. 2.145–2.180). The reaction representing the change is—

$$4Mg(OH)_2+3CO_2=Mg_2(CO_3)_3.2Mg(OH).3H_2O+k.$$

The increase in volume is 73.08 per cent. The alteration is therefore one of simple carbonation, and takes place in the zone of katamorphism, especially in the belt of weathering, with expansion of volume and liberation of heat.

GIBBSITE.

Occurrence.—Gibbsite occurs as an accessory constituent in many of the schists and gneisses, especially those which have been subjected to the forces of the upper physical-chemical zone, and particularly in the belt of weathering. As noted on subsequent pages, it may be a result of the alteration of many minerals, the more important of which are as follows: Anorthoclase, andalusite, biotite, cancrinite, corundum, cyanite, epidote, haüynite, microcline, muscovite, nephelite, noselite, orthoclase, phlogopite, plagioclases, pyrope, the scapolites, sillimanite, sodalite, topaz, tourmaline, and zoisite. By reference to the discussion of these minerals and the minerals which simultaneously form, the conditions of its formation may be ascertained.

Alterations.—No alterations of gibbsite are recorded in the standard text-books, but where sedimentary rocks containing gibbsite are so deeply buried as to pass into the zone of anamorphism it may become partly dehydrated, producing diaspore (orthorhombic; sp. gr. 3.40), or wholly dehydrated, producing corundum (rhombohedral; sp. gr. 4.025); or the aluminum may unite with other compounds, producing the same minerals that are produced by corundum or diaspore. It is believed that these

alterations from diaspore and gibbsite have taken place on an extensive scale, even if they have not been recorded. There is no doubt about the formation of gibbsite abundantly in the zone of katamorphism, especially in the belt of weathering. To my mind there is as little doubt that the widespread corundum of the schists, gneisses, and marbles is derived in large measure from gibbsite. I am confident that the hydrous aluminum oxides furnish the bases for much of the spinel (isometric; sp. gr. 3.80), sillimanite (orthorhombic; sp. gr. 3.235), and cyanite (triclinic; sp. gr. 3.615) which occur in these rocks. And it is little short of a certainty that gibbsite furnishes alumina for the silicates, muscovite (monoclinic; sp. gr. 2.88), margarite (monoclinic; sp. gr. 3.035), and zoisite (orthorhombic; sp. gr. 3.31). As with diaspore, the reactions producing all the above-mentioned silicates are those of dehydration and silicification. The following equations may be written for the above supposed reactions:

(1) $Al(OH)_3 = AlO(OH) + H_2O - k.$
(2) $2Al(OH)_3 = Al_2O_3 + 3H_2O - k.$
(3) $2Al(OH)_3 + MgCO_3 = MgAl_2O_4 + CO_2 + 3H_2O - k.$
(4) $2Al(OH)_3 + SiO_2 = Al_2SiO_5 + 3H_2O - k.$
(5) $6Al(OH)_3 + 6SiO_2 + K_2CO_3 = 2H_2KAl_3Si_3O_{12} + CO_2 + 7H_2O - k.$
(6) $4Al(OH)_3 + 2SiO_2 + CaCO_3 = H_2CaAl_4Si_2O_{12} + CO_2 + 5H_2O - k.$
(7) $6Al(OH)_3 + 6SiO_2 + 4CaCO_3 = H_2Ca_4Al_6Si_6O_{26} + 4CO_2 + 8H_2O - k.$

Regarding all the minerals as solid, the decrease of volume for diaspore (1) is 46.82 per cent; for corundum (2), 61.81 per cent; for spinel (3), 60.12 per cent; for sillimanite (4), 43.68 per cent; for cyanite (4), 49.61 per cent; for muscovite (5), 64.99 per cent; for margarite (6), 38.92 per cent; for zoisite (7), 43.06 per cent. The decreases of volume are greater for the corresponding minerals than for diaspore because of the greater amount of water in the gibbsite. In all the reactions heat is absorbed. The reactions are therefore typical of the zone of anamorphism.

THE CARBONATES.

The important carbonates which occur as rock-making constituents are the calcite group, including calcite, dolomite, ankerite and parankerite, magnesite, and siderite, and the aragonite group, of which aragonite is the only important rock-making member.

CALCITE GROUP.

CALCITE, DOLOMITE, ANKERITE, PARANKERITE, MAGNESITE, AND SIDERITE.

Calcite:
$CaCO_3$.
Rhombohedral.
Sp. gr. 2.713–2.714.

Dolomite:
$CaMgC_2O_6$.
Rhombohedral.
Sp. gr. 2.8–2.9.

Ankerite:
$CaFeC_2O_6.CaMgC_2O_6$;($CaMgC_2O_6$:$CaFeC_2O_6$::½:1 to 2:1).
Rhombohedral.
Sp. gr. 2.95–3.1.

Parankerite:
$CaFeC_2O_6.2CaMgC_2O_6$;($CaMgC_2O_6$:$CaFeC_2O_6$::2:1 to 10:1).
Rhombohedral.
Sp. gr. 2.95–3.1.

Magnesite:
$MgCO_3$.
Rhombohedral.
Sp. gr. 3.00–3.12.

Siderite:
$FeCO_3$.
Rhombohedral.
Sp. gr. 3.83–3.88.

CALCITE.

Occurrence.—The chief sources of calcite are (1) organic precipitates, (2) chemical precipitates, (3) by alteration of aragonite, and (4) by carbonation of silicates.

The chief direct source of calcite is organic. Corals and innumerable other kinds of shell animals, especially in the sea, abstract calcium carbonate from the water and build it into their external or internal structures. Calcite as a chemical precipitate may be deposited from the waters of the sea, especially in inclosed lagoons; by the waters of inland lakes, especially those having no outlet; by springs and streams, especially hot springs and desert streams; and by underground waters in the openings of rocks, such as the interstices between grains, the cavities of porous igneous rocks, especially amygdules, and in cave, fault, joint, and fissility openings. The deposited calcite may replace a considerable number of other minerals. As a deposit in the openings of rocks calcite is second in abundance only to quartz. Calcite is an alteration product of a large number of minerals, of which the following are the more common: Actinolite, ankerite, antho-

phyllite, aragonite, augite, diopside, dolomite, epidote, fluorite, garnet, grossularite, gypsum, haüynite, hornblende, noselite, parankerite, pyrope, sahlite, scapolites, tremolite, and zoisite.

While the abundant direct sources of calcite are (1), (2), and (3) above, the indirect and ultimate source which has probably furnished the great quantity of calcium carbonate is the carbonation of the silicates. (See pp. 473–480.) This process occurs on a great scale in the zone of katamorphism, especially in the belt of weathering. It is a reaction which takes place with liberation of heat and increase of volume in case the replaced silica separates as quartz in situ. Many of the individual carbonation reactions of the silicates, as, for instance, wollastonite, diopside, etc., are given under that class of minerals.

Alterations.—The first of the alterations of calcite is recrystallization. Calcite is the most mobile of the abundant rock-making minerals. It responds readily to changes of physical conditions, and is very susceptible to weak chemical agents. A slight stress may produce in it twinning structure. A state of unequal strain favors its solubility. Where the pressure increases, solution increases; where pressure is lessened, deposition takes place. Increase of temperature greatly increases its solubility, and vice versa. The increase of carbon dioxide in water greatly increases its solubility, and vice versa. Thus it happens that in rocks where the calcite is almost constantly subjected to changing pressure, temperature, and varying amounts of carbon dioxide it is constantly being taken into solution and, after a greater or less journey, being deposited from solution or carried to the sea to be ultimately precipitated by organic agents. The recrystallization of great masses of calcite, the solution of calcite in the belt of weathering and its partial deposition in the belt of cementation, the formation of caves, cave deposits, etc., are considered later.

The second important change of calcite is partial replacement of calcium by magnesium, often producing dolomite (rhombohedral; sp. gr. 2.8–2.9). The generalized reaction is:

(1) $2CaCO_3+Mg=CaMg(CO_3)_2+Ca+k.$

Supposing the calcium to be present as a carbonate, and supposing the added magnesium to be a chloride—and this is believed to be a very common case—the reaction would be:

(2) $2CaCO_3+MgCl_2=CaMgC_2O_6+CaCl_2+k.$

Or supposing that the magnesium salt is a carbonate, and that this is deposited and an equivalent amount of calcium carbonate is taken into solution, the reaction would be:

(3) $2CaCO_3+MgCO_3=CaMgC_2O_6+CaCO_3+k.$

Either of these changes is accompanied by the decrease in volume of 12.30 per cent if the original calcite be compared with the produced dolomite. There might be no diminution in volume, or even an increase in volume, in case less than the molecular weight of calcium salt equivalent to the introduced magnesium was dissolved. For instance, in an extreme case the reaction might be:

(4) $CaCO_3+MgCO_3=CaMg(CO_3)_2+k,$

the $MgCO_3$ being added through solutions, and no calcium carbonate dissolved. In this case the expansion in volume over the original calcite would be very great—75.41 per cent. However, the normal case in dolomitization, as noted below, appears to be the molecular replacement represented by the specific equations (2) and (3). The compounds concerned in these reactions are so important that the heat relations have been determined as above given; so it can be asserted positively, from chemical studies, that heat is liberated by them.

The calcium of calcium carbonate may be replaced by other metals besides magnesium, or calcite may be replaced by an oxide. The most important of the elements which enter into such combinations, and the only one which need be mentioned, is iron. At many localities, partly or wholly occupying the place once held by calcite, iron carbonate is found. For any definite proportion of iron replacing the calcium, equations may be written paralleling those for the replacement of calcium by magnesium.

The third important alteration of calcite is to wollastonite (monoclinic; sp. gr. 2.8–2.9). This alteration is, indeed, the chief source of wollastonite. The equation is:

(5) $CaCO_3+SiO_2=CaSiO_3+CO_2-k.$

In the change the volume is decreased 31.48 per cent, provided the silica used is a solid and the carbon dioxide escapes. In case the silicic acid be brought in solution from an outside source, the volume of the solid is increased 10.81 per cent. Between these extremes there are theoretically

all gradations, but, as noted below, an approach to the former extreme probably is the common case.

Recrystallization of calcite and dolomitization take place on the most extensive scale at all depths and under both mass-static and mass-dynamic conditions; they are therefore alterations which are common to both physical-chemical zones. By dolomitization it is believed that great masses of calcite have been transformed to dolomite. The evidence of this transformation and the detailed facts in connection with the change are given under dolomite. (See pp. 798–808.) The fact that dolomite forms in both zones would be sufficient evidence that the reactions producing this compound liberate heat, even if this had not been experimentally determined to be the fact. It has been pointed out before (pp. 181–182) that the formation of dolomite is a typical illustration of an alteration in which both the volume and the chemical changes liberate heat, and which therefore may occur in all zones and belts of the lithosphere.

The change from calcite to wollastonite occurs chiefly or wholly in the very deep-seated rocks, especially in the zone of anamorphism. In this zone, as noted (pp. 764–766), it can not be assumed that material is added in considerable quantity from an outside source by circulating water; hence in this zone silica for the change is believed to have been a solid. The reaction is therefore one taking place with the absorption of heat and condensation of volume. The silication of calcite to wollastonite in the zone of anamorphism may be taken as a typical example of the heat and volume change of silication of carbonates in that zone.

DOLOMITE.

Occurrence.—The chief source of dolomite is believed to be the dolomitization of calcite (see pp. 238–239), but dolomite is also a direct chemical precipitate. Dolomite also forms in subordinate amount by the alteration of ankerite. The ultimate source of the magnesium carbonate for the dolomitization of the calcite is the magnesium liberated by the carbonation of the silicates in the zone of katamorphism, especially in the belt of weathering. The reactions for the decomposition of some of the simple silicates, such as diopside and tremolite, are given under those minerals. The magnesium for the dolomitization need not be directly derived from a silicate, but may be from the solutions of the sea or from

a previously formed magnesium limestone or dolomite which is in the belt of weathering. Dolomite produced by the carbonation of the silicates or by solution of dolomitic formations is an important chemical precipitate in caves and small crevices in the rocks, the same as calcite.

In summary, dolomite is chiefly derived as a secondary mineral from ankerite, calcite, and parankerite.

Alterations.—An important alteration of dolomite is to diopside (monoclinic; sp. gr. 3.2–3.38). This alteration is a typical example of silication. (See p. 205.) The most probable reaction is:

(1) $MgCaC_2O_6+2SiO_2=MgCaSi_2O_6+2CO_2-k.$

The decrease in volume is 40.11 per cent, provided all of the silica entering into the combination was a solid. In case all of the silica were introduced through water solutions there would be an increase in volume of 2.03 per cent. More important alterations of dolomite are into tremolite (monoclinic; sp. gr. 2.9–3.1) and calcite (rhombohedral; sp. gr. 2.713–2.714), or into tremolite and wollastonite (monoclinic; sp. gr. 2.8–2.9). In the first case the reaction is:

(2) $3CaMgC_2O_6+4SiO_2=Mg_3CaSi_4O_{12}+2CaCO_3+4CO_2-k.$

The decrease in volume, provided the silica is present as a solid, the calcite remains as a solid, and the carbon dioxide escapes, is 25.20 per cent. However, the excess of calcium carbonate may simultaneously change to wollastonite. In this case the reaction would be:

(3) $3CaMgC_2O_6+6SiO_2=Mg_3CaSi_4O_{12}+2CaSiO_3+6CO_2-k.$

The decrease in volume as compared with the dolomite and quartz of the tremolite and wollastonite is 33.09 per cent. In both of the changes, if a portion of the silica be supposed to be introduced from an outside source the decrease in volume would be lessened, and if all of it were thus supposed to be introduced there would be an increase in volume from the solid dolomite of 9.89 per cent in the case of tremolite and calcite, and 14 per cent in the case of tremolite and wollastonite.

The space once occupied by dolomite, like that occupied by calcite, may be taken by other carbonates or by various oxides. The most important of these are carbonate of iron and oxide of iron. The carbonate may be a replacement, or possibly a substitution, of the iron of some other iron

salt for that of the calcium and magnesium. The oxide of iron is an illustration of a pure replacement, not of an alteration.

The formation of diopside, tremolite, and wollastonite is known to occur in deep-seated rocks, and especially in connection with mass-mechanical action where the rocks are deformed by flowage. As repeatedly noted, in the zone of anamorphism the circulation of water is reduced to a minimum; and it can not be supposed that important additions are made from the outside, and therefore the silica must be supposed to have been previously present in the rocks. Indeed, we know that silica usually accompanies deposits of calcite and dolomite; hence I conclude that the reactions take place with substantially the decrease in volume above assigned to the changes. In the reactions heat is absorbed. The changes are therefore again typical illustrations of silication in the lower physical-chemical zone.

ANKERITE AND PARANKERITE.

Occurrence.—All the compounds from normal ankerite and parankerite to the extremes of composition given above (p. 237) are included under the general term ferro-dolomite, which I have elsewhere used as covering all the ferriferous compounds standing between dolomite on the one side and siderite on the other. (See p. 823.)

The sources of ankerite and parankerite are the same as siderite, with the difference that at the time of the formation of the iron carbonate, calcium and magnesium carbonate are present, or formed, and unite with it.

Alterations.—The more common alterations of ankerite and parankerite are to limonite (amorphous; sp. gr. 3.80), hematite (rhombohedral; sp. gr. 5.225), and magnetite (isometric; sp. gr. 5.174), the calcium and magnesium carbonates either separating or simultaneously undergoing the alterations given under "Calcite" and "Dolomite." Equations may easily be written for any definite compound by which the iron carbonate passes into the minerals mentioned in the same way that siderite does and the calcium-magnesium carbonates separate. The volume changes are in the same direction, and the physical conditions under which ankerite and parankerite alter to limonite, hematite, and magnetite are the same as those for the alteration of siderite to the like compounds. Therefore the equations and summary of physical conditions will not be here repeated.

Other important alterations of the ferro-dolomites are to sahlite (mono-

clinic; sp. gr. 3.25–3.4) and to actinolite (monoclinic; sp. gr. 3.00–3.20). Supposing that the magnesium and iron are present in equal quantity in the sahlite, the reaction in the case of normal ankerite is:

(1) $CaFeC_2O_6.CaMgC_2O_6+4SiO_2=MgFeCa_2Si_4O_{12}+4CO_2-k.$

Supposing the silica to be present as a solid, the decrease in volume is 37.27 per cent. In the formation of actinolite from normal ankerite, on the supposition that the iron and magnesium are present in equal quantity in the actinolite, the reaction is:

(2) $3CaFeC_2O_6.CaMgC_2O_6+8SiO_2=Mg_3Fe_3Ca_2Si_8O_{24}+4CaCO_3+8CO_2-k.$

The decrease in volume, supposing the silica to be present as a solid and the $CaCO_3$ as a solid, is 22.62 per cent. Of course, if the ferro-dolomite were one in which the calcium carbonate is not so plentiful, being replaced in equal molecular parts by magnesium and iron, it would not be necessary for any calcium carbonate to form as a result of the reaction. For instance, if the ferro-dolomite were $CaFe_3C_4O_{12}.CaMg_3C_4O_{12}$ the reaction would be as follows:

(3) $CaFe_3C_4O_{12}.CaMg_3C_4O_{12}+8SiO_2=Mg_3Fe_3Ca_2Si_8O_{24}+8CO_2-k.$

Using the specific gravity of normal ankerite, the decrease of volume of the actinolite as compared with the ankerite and quartz is 32.72.

Sahlite and actinolite are both known to form abundantly in the zone of anamorphism. Sahlite is found in the marbles of eastern United States. Actinolite is very abundant in the iron-bearing formations of the Lake Superior region. The development of these silicates may be taken as typical illustrations of the reaction of silication in the lower physical-chemical zone, with condensation of volume and absorption of heat.

MAGNESITE.

Occurrence.—Magnesite may be a product of the alteration of any of the heavily magnesian rocks. It is especially prevalent in the olivinitic rocks and the chloritic, serpentinous, and talcose schists and gneisses, being a product which is produced by the alteration of original minerals simultaneously with the formation of chlorite, serpentine, and talc. It is also found in dolomite. The more important minerals from which it is recorded as forming are common garnet, olivine, pyrope, and serpentine.

Alterations.—No alterations are recorded for magnesite. There is, however, no doubt that this compound does break up in the zone of anamor-

ism, the carbon dioxide being liberated and the magnesia being furnished for the formation of various dense magnesian minerals, such as enstatite, tremolite, olivine, pyrope, etc. These changes would involve a diminution of volume and an absorption of heat.

SIDERITE.

Occurrence.—The chief source of siderite is believed to be the reduction, dehydration, and carbonation of limonite. (See pp. 233–234.) This change is one occurring with the liberation of heat if the reaction upon the organic compound be taken into account, and increase of volume. A subordinate amount of siderite is also derived from magnetite. This change takes place with liberation of heat and increase of volume. Siderite also forms from ankerite and parankerite, arfvedsonite, garnet, hematite, horublende, hydrous ferrous silicate, limonite, magnetite, and olivine, and replaces calcite and dolomite.

Alterations.—The important alterations of siderite are into limonite (amorphous; sp. gr. 3.6–4.0), hematite (hexagonal-rhombohedral; sp. gr. 5.225), magnetite (isometric; sp. gr. 5.168–5.18), and grünerite (monoclinic; sp. gr. 3.713). The reactions are as follows:

(1) $4FeCO_3+2O+3H_2O=2Fe_2O_3.3H_2O+4CO_2+k.$

The decrease in volume is 18.22 per cent.

(2) $2FeCO_3+O=Fe_2O_3+2CO_2+k.$

The decrease in volume is 49.11 per cent.

(3) $3FeCO_3+O=Fe_3O_4+3CO_2+k.$

Very often iron sulphide, as pyrite (isometric; sp. gr. 5.025) or marcasite (orthorhombic; sp. gr. 4.875), unites with the siderite to form magnetite. This reaction is probably of great consequence in forming the heavy beds of magnetite. (See p. 845.) It may be written:

(4) $2FeCO_3+FeS_2+2H_2O=Fe_3O_4+2H_2S+2CO_2-k.$

The decrease in volume for the siderite alone to the magnetite, equation (3), is 50 32 per cent; for siderite and pyrite, 46.67 per cent; for siderite and marcasite, 47.135 per cent.

(5) $FeCO_3+SiO_2+nH_2O=FeSiO_3+CO_2+nH_2O-k.$

The decrease in volume, regarding the silica as a solid, is 32 53 per cent.

The alteration to limonite occurs in the zone of katamorphism, especially

in the belt of weathering. The alteration to hematite occurs as a somewhat deeper-seated change, usually in the belt of cementation of the zone of katamorphism. The alteration to magnetite is especially characteristic of the zone of anamorphism, but it can not be asserted not to take place in the belt of cementation. The alteration to grünerite occurs under deep-seated conditions, and is in its heat and volume relations a characteristic reaction of the lower zone. Magnetite and grünerite often form simultaneously. (See p. 284) The series of changes from siderite are very interesting, in that the volume changes are all diminutions, and therefore, so far as this factor is concerned, might take place in either zone. The first three reactions (equations 1, 2, and 3) liberate heat, and hence these reactions in their physical-chemical relations are similar to those of dolomite, discussed on pages 182, 240, and may take place in both zones. But the reaction of equation (4) probably absorbs heat, and that of (5) certainly does. Magnetite having the origin represented by equation (4) is probably, and grünerite is certainly, confined to the zone of anamorphism, where pressure is a controlling factor.

ARAGONITE GROUP.

The only important rock-making member of this group is aragonite.

ARAGONITE.

Aragonite:
$CaCO_3$.
Orthorhombic.
Sp. gr. 2.93–2.95.

Occurrence.—A chief source of aragonite is as an organic precipitate. It occurs intimately associated with calcite in numerous marine shells. While abundant, it is very subordinate to calcite as an organic deposit. A second abundant source of aragonite is as a chemical precipitate, frequently in association with beds of iron carbonate and gypsum. It also occurs as a chemical precipitate from ground-water solutions, in openings in rocks, especially at places where the temperature of the solutions is from 30° to 100° C. or more. Aragonite is not mentioned as an alteration product of other minerals.

Alterations.—The chief change of aragonite is to calcite (rhombohedral; sp. gr. 2.713–2.714). This is a change involving recrystallization, increase of symmetry, and lowering of specific gravity. The increase in volume is 8.35 per cent. The heat effect of the change has not been found; but it

seems probable that heat is liberated, for the transformation of aragonite to calcite occurs in both the physical-chemical zones, and I know of no exception to the principle that such reactions take place under the first part of van't Hoff's law (see pp. 107, 181).

The change from aragonite to calcite is so complete in rocks of moderate age that the presence of aragonite in the metamorphosed rocks is almost unknown. The alteration of aragonite to calcite in both zones is of considerable interest, as it presents a somewhat exceptional case. As explained on pages 182–186, the common rule of change in the zone of anamorphism is increase in specific gravity and increase of symmetry, provided the volume change demanded will allow this. However, the change of specific gravity in this case is a decrease rather than an increase, and hence aragonite conforms only to the second of these rules—the first, and usually the controlling rule, for the zone of anamorphism being violated. These facts suggest the conclusion that in this instance symmetry is a more important factor than density—a very exceptional thing. If this be so, the conclusion would follow that the symmetrical arrangement of the molecules in calcite are those which best resist the changing conditions of mass-static and mass-mechanical action in the lower zone The suggestion occurs to one that, if rocks were very deeply buried, so as to be extraordinarily deep in the lithosphere, pressure might control the form, and calcite alter to aragonite. This, however, is a speculation which has no verification.

THE SILICATES.

The silicates are the most important of rock-making constituents. They include natural glass and many mineral groups. The groups of rock-making silicates are as follows: Feldspar, leucite, pyroxene, amphibole, nephelite, sodalite, garnet, chrysolite, scapolite, zircon, aluminum-silicate, epidote, humite, zeolite, mica, clintonite, chlorite, serpentine-talc, and kaolin. Besides the members of the above groups are a number of important rock-making silicates not so included.

GLASS.

Glass, while not a definite silicate or ordinarily included among the specific minerals, is an important rock-making constituent, and therefore must be treated in connection with the silicates in a treatise on metamorphism.

Occurrence.—Natural glass is an abundant constituent of the effusive rocks. It is especially prevalent in the more acid ones, but is not confined to them, being not infrequently abundant in the intermediate rocks, such as basalts. A lava or tuff may be almost wholly composed of glass, or glass may constitute but a small part of the background. There are thus all gradations between completely crystalline rocks and glassy rocks. Of the more recent effusive rocks glass not infrequently composes a large part of the flows. An instance is Obsidian Cliff, in the Yellowstone National Park. But in proportion as lavas are old, glass is less and less likely to be found, and in the more ancient lavas is ordinarily absent. The explanation of this absence is devitrification after solidification.

Evidence that devitrification takes place.—That certain rocks now wholly composed of minerals were once glasses is shown by the preservation in perfection of the flow structures and very delicate trichitic, perlitic, spherulitic, and other textures characteristic of glass.

Scale of devitrification.—It is also certain that the process of devitrification has taken place in nature on a great scale. As evidence of this may be cited the well-known American instances of devitrified glass in the original Huronian district, described by Williams,[a] the aporhyolite of South Mountain, Pennsylvania, described by Williams and Bascom,[b] the metarhyolites of the Fox River Valley of Wisconsin, described by Weidman,[c] and the devitrified glasses of the Crystal Falls district of Michigan, described by Clements.[d] In the papers of these authors many other instances of devitrification are cited, including European instances.

Not only does devitrification of natural glass take place, but under proper conditions artifical glass devitrifies in a similar manner. Well-known cases of the devitrification of artificial glass under conditions of weathering are those of the buried ancient glasses of Nineveh and of Rome.

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[a] Williams, G. H., Notes on the microscopical characters of rocks from the Sudbury mining district, Canada: Ann. Rept. Geol. and Nat. Hist. Survey of Canada, vol. 5, Pt. F, Appendix 1, 1890–1891, pp. 74–82.

[b] Williams, G. H., The volcanic rocks of South Mountain, in Pennsylvania and Maryland: Am. Jour. Sci., 3d ser., vol. 44, 1892, pp. 486–490.

Bascom, Miss Florence, The ancient volcanic rocks of South Mountain, Pennsylvania: Bull. U. S. Geol. Survey No. 136, 1896, pp. 42–61.

[c] Weidman, Samuel, A contribution to the geology of the pre-Cambrian igneous rocks of the Fox River Valley, Wisconsin: Bull. Wisconsin Geol. and Nat. Hist. Survey No. 3, 1898, pp. 4–31.

[d] Clements, J. Morgan, and Smyth, H. L., The Crystal Falls iron-bearing district of Michigan: Mon. U. S. Geol. Surv., vol. 36, 1899, pp. 87, 101–103, 138.

In glass found in the lake at Walton Hall, near Wakefield, Bingley[a] found that the alkalies had been wholly removed by decay. Another case of devitrification largely due to original state of strain is the glass of certain old buildings, such as cathedrals. A well-known instance is that of St. Andrew's Chapter House.[b]

Rate of devitrification.—The rate of devitrification of glass depends, among other things, upon (1) composition, (2) strain or lack of strain, (3) pressure, (4) mass-mechanical action, (5) temperature, (6) moisture.

In any given case of devitrification several and sometimes all of these factors enter, and hence it is impossible to discriminate the effect of each. Very often devitrification has been described as hydro-metamorphism, but by this no more can be meant than that water is usually an important factor in the process.

(1) The rate of devitrification of glass increases with its basicity. This follows from the ready solubility of basic glasses. It has also been determined that glasses rich in soda devitrify faster than those rich in potash. This corresponds with the fact emphasized in another place (see p. 516) that minerals rich in soda are more readily decomposed than those rich in potash.

(2) It is shown in another place that a state of strain in minerals promotes alteration. (See pp. 95–98.) The same is true of glass. It is definitely known that unannealed glass, which therefore cooled irregularly and is in a state of strain, independently of pressure or movement may partly devitrify in a few years. For instance, drawn-glass tubing, such as is used in the chemical laboratory, if kept for a few years may devitrify so as to become useless. Another well-known case of devitrification probably due to strain is the glass of certain cathedral windows. As large masses of glass cool under natural conditions, they must often be almost at the extreme of the unannealed condition, and therefore in a high state of strain. So far as glass is in this condition, even without reference to any extraneous pressure or movement, there is a marked tendency toward devitrification. The stage of the process due to this cause is dependent upon the amount of strain and the time.

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[a] Bingley, C. W., On the peculiar action of mud and water on glass, as more especially illustrated by some specimens of glass found in the lake at Walton Hall, near Wakefield: Rept. Twenty-eighth Meeting British Assoc. Adv. Sci., London, 1859, pp. 45–46.

[b] Brewster, Sir David, On the decomposition of glass: Rept. Tenth Meeting British Assoc. Adv. Sci., London, 1841, pp. 5–7.

(3) Pressure produces a state of unequal strain, and hence is favorable to devitrification.

(4) Mass-mechanical action not only produces a state of unequal strain in minerals, but fractures the material, and this gives a large surface of action for the solutions. It is therefore clear that mass-mechanical action is very favorable to devitrification.

(5) Experiments in the laboratory show that if glass be raised to a temperature short of fusion the tendency to devitrification is greatly promoted. It is therefore certain that conditions of dry heat after solidification are favorable to devitrification. As glass occurs in considerable bodies in a state of nature, it must for a long time, perhaps hundreds of thousands of years, have a high temperature due to the residual heat of the magma, and only very gradually assumes the normal temperature corresponding with its depth of burial. It is rather probable that microlites and crystallites, which so frequently occur in glass, largely form during this process of cooling after solidification.

(6) While devitrification of glass may occur without the presence of abundant water, it is probably rare indeed that in nature the process occurs without the presence of some moisture, and in general moisture is a very important factor favorable to devitrification.

It is therefore clear that each of the above factors may give a condition favorable to devitrification, but in general actual devitrification is due to a combination of two or more of them.

Devitrification in the two zones.—In the zone of katamorphism under ordinary conditions it is probable that the devitrification occurs somewhat slowly. But in areas of regional volcanism, and often in those of local volcanism, the lava flows follow one another in such rapid succession that beds are piled up so deep that the water is held at a high temperature. By complex intrusion the entire mass of a cooled glass may again be raised to a high temperature. Orogenic movement if severe may produce a high temperature. Under any of these circumstances the conditions are furnished for the complete and rapid devitrification of the glass.

The nature of the devitrification is certainly different in the belt of weathering and the belt of cementation, although available descriptions do not furnish data for accurate statements as to the differences. But it is certain that in the belt of weathering the several changes are along the

lines given on pages 506–527 for that belt, finally resulting in the obliteration of textures and structures and producing an incoherent rock.

In the belt of cementation ordinarily the alterations do not result in the obliteration of the original textures and structures of the glasses. This is sufficiently evident where the alterations occur under mass-static conditions, and even where mass-mechanical conditions prevail. The glass is simply fractured, as explained on pages 601–602, and the individual blocks are altered by metasomatism under mass-static conditions.

So far as we know, glasses originally form only in the zone of katamorphism, and mainly at or near the surface. Therefore a glass can get into the zone of anamorphism only by being buried under succeeding lava flows or tuffs or under sedimentary rocks. Hence, before glass reaches the lower zone, it must have been subjected for a long time to devitrification in the belt of cementation, and the question arises whether or not a glass would not be completely devitrified before it becomes sufficiently deeply buried to reach the zone of anamorphism. However, if glass ever does reach the lower zone, it is certain that its devitrification will take place rapidly under either mass-static or mass-mechanical conditions. The rocks in this lower zone are everywhere at temperatures exceeding 100° C; they contain water; hence, even under conditions of absolute quiescence, it is certain that glass could not long exist. The crystallization would be even more rapid under mass-mechanical conditions.

In so far as the glass had devitrified in the zone of katamorphism, and had produced minerals characteristic of that zone, in the lower zone these minerals would be recrystallized and minerals formed characteristic of the latter zone. If mass-static conditions prevail this recrystallization may take place without obliterating previous textures and structures. However, if recrystallization takes place under conditions of mashing, the original textures and structures are lost, and minerals are produced of such kinds and proportions as correspond with the composition of the glass. Moreover, when the glass passes into the zone of anamorphism, textures and structures may be formed characteristic of the slates, schists, and gneisses. When such alteration is complete it is often impracticable to determine whether the rock was originally glass or not. There can be little doubt that many of the finer-grained schists are derived from rocks which were

originally partly or wholly glassy. For instance, the Berlin gneiss of central Wisconsin is in chemical composition the same as that of various associated aporhyolites. The aporhyolites show that they were originally glasses by retaining the characteristic textures of glass. The Berlin gneiss which was altered under conditions of mashing in the deep-seated zone is entirely devoid of any structure which can be attributed to glass, and one can not be certain that it did originally have a glassy base, although this seems probable.

Minerals produced.—The minerals which are produced by the alterations of glass are very numerous. It has already been noted that glasses form from the most acid magmas, and also from those which are intermediate or basic in character. Furthermore, it has been seen that glass is devitrified in both the upper and the lower physical-chemical zones, and in the upper zone both in the belt of weathering and in that of cementation. In each of these zones and belts minerals form from the glass which are characteristic of them. It is plain from the foregoing that every mineral which may be a metamorphic product of an igneous rock of any kind may result from the devitrification of glasses of different kinds under the different conditions which obtain in the zones and belts of alteration.

Heat and volume relations.—The devitrification of glass is a process which probably results in the liberation of heat. This is certainly true for the zone of katamorphism, where oxidation, hydration, and carbonation take place. As to the volume relations of the change, the devitrification itself by means of which the substance passes from an amorphous to a crystalline condition would decrease the volume, provided there were no additions of other compounds. But where devitrification is accompanied by oxidation, carbonation, and hydration there are considerable additions of material. Therefore, in the belt of cementation there can be little doubt that expansion of volume is the rule where glasses are devitrified; but in the belt of weathering, where solution is prominent, doubtless there is diminution in volume with glass as with other compounds. In the zone of anamorphism devitrification takes place with decrease of volume, the reactions being controlled by pressure. Whether heat be liberated or absorbed in the zone of anamorphism doubtless depends in large measure upon how far the reactions of the zone of katamorphism have taken place during the time

the glass was passing through that zone. If these had gone far, the undoing of the oxidation, hydration, and carbonation would probably absorb heat. But if the glass reached the zone of anamorphism in an anhydrous condition, the crystallization, producing a decrease in volume, would liberate heat. Thus no general statement can be made as to the heat reaction in the zone of anamorphism.

FELDSPAR GROUP.

The minerals of the feldspar group are the most abundant of the silicates. According to Clarke,[a] the feldspars comprise 60 per cent of the minerals of the lithosphere. The feldspars include minerals of two classes of symmetry, monoclinic or pseudomonoclinic, and triclinic. Those of the first class comprise orthoclase, microcline, and anorthoclase; those of the second class include albite, oligoclase, andesine, labradorite, bytownite, and anorthite.

In chemical composition the feldspars vary from orthosilicates, through metasilicates, to polysilicates. The readiness of decomposition is indirectly proportional to the acidity, the orthosilicates being the most easily decomposed, and the polysilicates being the most difficult to decompose.

The more frequent alterations of the monoclinic feldspars and of the polysilicate plagioclase feldspars are to mica, especially muscovite, and to hydrated silicate of aluminum, especially kaolin. In this alteration there is simultaneous liberation of silica, which may separate as quartz. Very frequently also gibbsite is formed at the same time. Where the mica biotite is produced it is necessary that iron and magnesium shall be added. The most common alterations of the orthosilicate plagioclase feldspars are to zeolites, epidote, and zoisite, frequently with the simultaneous formation of another plagioclase and chlorite. Where epidote is produced it is necessary that iron be added from some other source; where chlorite is produced it is necessary that magnesium and iron be added from some other source. All the important minerals produced by the alterations of the feldspars, with the exception of quartz and plagioclase, are hydrated, though in varying degrees; hence, in general, water is added during the alteration of the feldspars. From the intermediate plagioclases there may be produced any of the foregoing minerals

[a] Clarke, F. W., Analyses of rocks, laboratory of the U. S. Geol. Survey, 1880–1899: Bull. U. S. Geol. Survey No. 168, 1900, p. 16.

MONOCLINIC OR PSEUDOMONOCLINIC.

ORTHOCLASE, MICROCLINE, AND ANORTHOCLASE.

Orthoclase:
$KAlSi_3O_8$.
Monoclinic.
Sp. gr. 2.57.

Microcline:
$KAlSi_3O_8$.
Triclinic.
Sp. gr. 2.54–2.57.

Anorthoclase:
$mNaAl_2Si_3O_8.nKAl_2Si_3O_8$. (Na-silicate:K-silicate:: 2:1 or 3:1, usually.)
Pseudomonoclinic or triclinic.
Sp. gr. 2.57–2.60.

ORTHOCLASE AND MICROCLINE.

Occurrence.—Orthoclase and microcline have a very widespread occurrence as chief pyrogenic constituents. The minerals also are allogenic constituents of the clastic rocks. They further have a very widespread occurrence in the metamorphic rocks, being chief constituents both as allogenic and as autogenic constituents of the schists and gneisses of both aqueous and igneous origin. In the development of the feldspars as autogenic constituents it is usually necessary that two or more minerals unite, except in the case of the derivation of the acid feldspars from the more basic ones or from leucite. As a metamorphic mineral orthoclase is derived from analcite, heulandite, leucite, laumontite, and stilbite. Microcline is recorded as derived from spodumene.

Alterations.—One of the most important alterations of orthoclase and microcline is to kaolinite (monoclinic; sp. gr. 2.60–2.63). The most probable reaction, for reasons given below, is believed to be:

(1) $2KAlSi_3O_8+2H_2O+CO_2=H_4Al_2Si_2O_9+4SiO_2+K_2CO_3+k.$

The decrease in volume, supposing the freed silica to separate as quartz, and K_2CO_3 dissolved, is 12.57 per cent. If all of the freed silica be dissolved, the decrease in volume would be 54 44 per cent. In calculating these volume changes and those which follow, the specific gravity of orthoclase is used.

While the ordinary alteration of the potash feldspars to the kaolin group is to kaolinite as indicated, the alteration may be to other minerals of this group; for instance, to pyrophyllite (monoclinic (?); sp. gr. 2.8–2.9), halloysite (massive; sp. gr. 2.1), newtonite (rhombohedral; sp. gr. 2.37),

cimolite (amorphous; sp. gr. 2.24), allophane (amorphous; sp. gr. 1.87), and perhaps others. The chief differences are in the amounts of water added and the amount of silica which separates. Pyrophyllite ($H_2Al_2(SiO_3)_4$) differs from kaolinite in that less silica is removed and less basic water is added; it therefore might be considered as an intermediate stage in the alteration. Halloysite ($H_4Al_2Si_2O_9$ Aq.) differs from kaolinite only in having water of hydration. Newtonite ($H_8Al_2Si_2O_{11}$.Aq.) differs from kaolinite in containing twice as much basic water as that mineral, and in being hydrated. Cimolite ($H_6Al_4(SiO_3)_9.3H_2O$) differs from kaolinite in containing more silica, more basic water, and water of hydration. Allophane ($Al_2SiO_5.5H_2O$) differs from kaolinite in containing less silica and much water. It would be easily possible to formulate equations along the line of that given for kaolinite for each of these minerals and to calculate the volume relations. However, this hardly seems necessary since these minerals as secondary products to orthoclase and microcline appear to be very subordinate in amount.

Another alteration of orthoclase and microcline of some little importance is into gibbsite (monoclinic; sp. gr. 2.3–2.4). The reaction is:

$$(2)\quad 2KAlSi_3O_8+3H_2O+CO_2=2Al(OH)_3+6SiO_2+K_2CO_3+k.$$

The decrease in volume of the gibbsite and quartz as compared with the orthoclase is 6.61 per cent.

Another of the very important alterations of orthoclase and microcline is to muscovite (monoclinic; sp. gr. 2.76–3.0) and quartz (rhombohedral; sp. gr. 2.653–2.654). The reaction is:

$$(3)\quad 3KAlSi_3O_8+H_2O+CO_2=KH_2Al_3Si_3O_{12}+6SiO_2+K_2CO_3+k.$$

Provided the silica separates as quartz and the potassium unites with carbonic acid and the potassium carbonate be removed in solution, the decrease in volume is 15.58 per cent.

While this reaction may take place under exceptional conditions, it is believed, as explained below, that where muscovite forms from orthoclase one of the rich aluminous minerals often unites with the orthoclase to produce the mica. Supposing the aluminous mineral to be gibbsite, the reaction is:

$$(4)\quad KAlSi_3O_8+2Al(OH)_3=KH_2Al_3Si_3O_{12}+2H_2O-k.$$

The decrease in volume of the muscovite as compared with the orthoclase and gibbsite is 20.81 per cent.

The alteration may be to hydro-muscovite or damourite (monoclinic; sp. gr. 2.76–3.00). This is believed by most mineralogists to differ from muscovite only in containing more water, but Dana states that a greater content of water in damourite than that contained by ordinary muscovite is not necessary.

From orthoclase and microcline, with the addition of magnesium and iron compounds, biotite (monoclinic; sp. gr. 2.7–3.1) may be formed. If the hydrogen and potassium be supposed to be present in equal proportions and the same supposition be made with reference to magnesium and iron, and the latter elements are supposed to be present as carbonates, the reaction may be as follows:

(5) $4KAlSi_3O_8+2MgCO_3+2FeCO_3+H_2O=$
$2HKMgFeAl_2Si_3O_{12}+5SiO_2+K_2SiO_3+4CO_2+k.$

The decrease in volume of the feldspar, magnesium carbonate, and iron carbonate in passing into the biotite and quartz is 22.64 per cent. But, as with muscovite, the more frequent reaction probably involves gibbsite, thus:

(6) $KAlSi_3O_8+MgCO_3+FeCO_3+Al(OH)_3=HKMgFeAl_2Si_3O_{12}+H_2O+2CO_2+k.$

This greatly simplifies the equation. The decrease in volume of the biotite as compared with the compounds from which it is derived is 22.33 per cent.

Orthoclase and microcline are said also to alter to epidote (monoclinic; sp. gr. 3.25–3.50); but if this be so calcium and iron must be introduced. The forms in which these compounds are present during the alteration are doubtless variable. If they be assumed to be present as calcium carbonate and iron sesquioxide, the reaction might be as follows:

(7) $4KAlSi_3O_8+Fe_2O_3+4CaCO_3+H_2O=2HCa_2Al_2FeSi_3O_{13}+6SiO_2+2K_2CO_3+2CO_2+k.$

Supposing the Al is to the Fe as 2 is to 1, the decrease in volume of the epidote and quartz as compared with the feldspar, calcite, and iron oxide together is 33.73 per cent. However it is so uncertain as to the forms of the accessory compounds, both before and after reaction, that it is impossible to make a definite statement as to the volume relations.

The alteration of orthoclase and microcline to minerals of the kaolin group and to gibbsite occurs in the zone of katamorphism. The process takes place on the most extensive scale in the belt of weathering, especially

in the soil horizon. Wherever the feldspathic rocks are exposed to atmospheric agencies this change steadily goes on, though not so rapidly as with the orthosilicate feldspars. (See p. 519.) But wherever the potash feldspars have been very long exposed to the weathering agencies they have been partly or wholly decomposed, and in some places to a depth of several hundred feet. The change is one of the most important of all those which affect rocks. It is partly because the alterations take place near the surface, where carbon dioxide is abundant, that it is believed that the freed alkali largely unites with carbon dioxide, as given in the reaction. The silica freed in the belt of weathering is in part undoubtedly taken into solution as colloidal silicic acid and carried downward to the belt of cementation. Indeed, the silica for the process of silicification in this belt, which, as explained on page 480, is derived from the decomposition of the silicates, probably in good part comes from the alteration of the feldspars. Under the same conditions in which a part of the feldspar breaks up into kaolinite another part of the feldspar may produce gibbsite, quartz, and potassium carbonate. The potassium carbonate liberated at the time of the formation of the kaolinite and gibbsite is largely dissolved and transported elsewhere, although the soluble potassium compounds are often held in the soil to a considerable extent. (See pp. 498, 541–543.)

The alteration of orthoclase and microcline to minerals of the kaolin group and to gibbsite is not, however, confined to the belt of weathering. It takes place on an important scale in the belt of cementation, though not on a scale comparable to that in the belt above. So far as known, kaolinization is not a reaction which occurs in the zone of anamorphism; at least, if it does there take place it is a very subordinate phenomenon. As seen above, the reaction is one taking place with liberation of heat and frequently with decrease of volume, since much and perhaps the most of the freed silica is taken away in solution. The heat reaction controls, and hence the change is under the rules of the upper physical-chemical zone.

The alteration of orthoclase and microcline to mica occurs in rocks which have been somewhat deeply buried, and the change has been noted in connection with both mass-static and mass-mechanical action. Under either of these conditions the alteration may be nearly or quite complete. But it has taken place on the most extensive scale in connection with mass-mechanical action, where the secondary structures, such as cleavage, are

produced, and therefore in the belt of rock flowage. In the formation of muscovite and quartz from feldspar by equation (3), as the specific gravity of the separated quartz is somewhat greater than that of the original feldspar, and that of the muscovite is considerably greater than that of the feldspar, the condensation in volume above calculated is accounted for, although the alteration is one involving hydration and possibly carbonation. In the zone of anamorphism the water added is doubtless largely derived from other minerals, as this is a belt of dehydration, and destruction of previous minerals containing hydroxides. This passage from one mineral to another would involve no increase in the total volume, the controlling consideration. The most doubtful point concerning equation (3) is the carbonation of the potassium. It might be supposed that the potassium unites with a part of the freed silica and with other elements to form potassium minerals. But it is not easy to suggest such minerals, as leucite is not recorded as a metamorphic mineral. The more probable solution of the problem is that potassium and a portion of the silica unite with the alumina of the gibbsite or some other minerals and produce one molecule of mica from one of orthoclase, as suggested in equation (4). This suggestion is rendered especially plausible for the slates, schists, and gneisses derived from sediments, for such rocks usually contain residual orthoclase and also aluminum hydroxide. (See pp. 232, 235, 898–900.) The reaction of equation (4) produces great decrease in volume, is one of dehydration, and thus absorbs heat; it is therefore a perfect example of the rules of the zone of anamorphism. The same remarks are applicable to equations (5) and (6), respectively, for the production of biotite, as to (3) and (4) for the formation of muscovite, with the addition that the development of biotite involves silication and decarbonation, and therefore still better than muscovite illustrates the reactions of the zone of anamorphism.

The physical-chemical principles for the alteration of orthoclase and microcline to epidote are the same as for the alterations of the more basic feldspars to epidote. As the process occurs much more extensively in connection with the latter minerals, it is discussed under the basic plagioclases. (See pp. 263–264.)

ANORTHOCLASE.

Occurrence.—This mineral is subordinate in quantity to orthoclase and microcline. It occurs in both deep-seated and effusive igneous rocks; in

the latter, chiefly in the andesitic lavas. As an allogenic mineral it also is found in the sedimentary rocks. Whether it occurs as an autogenic mineral in the metamorphic rocks has not been determined.

Alterations.—Both orthoclase and microcline contain some sodium. When the sodium becomes important the mineral is anorthoclase. It naturally follows from this fact that the alterations of anorthoclase are in all respects like those of orthoclase and microcline, with the exception that the freed alkalies are in good part sodium. The reactions are analogous to those already given for orthoclase, but with the muscovite or biotite the soda-mica paragonite (monoclinic; sp. gr. 2 84) is formed. Supposing the sodium silicate is to the potassium silicate as 2 to 1, the more important reactions may be written as follows:

(1) $2(2NaAlSi_3O_8.KAlSi_3O_8)+6H_2O+3CO_2=3H_4Al_2Si_2O_9+12SiO_2+K_2CO_3+2Na_2CO_3+k.$

(2) $2(2NaAlSi_3O_8.KAlSi_3O_8)+9H_2O+3CO_2=6Al(OH)_3+18SiO_2+K_2CO_3+2Na_2CO_3+k.$

(3) $2NaAlSi_3O_8.KAlSi_3O_8+6Al(OH)_3=KH_2Al_3Si_3O_{12}+2NaH_2Al_3Si_3O_{12}+6H_2O-k.$

(4) $2NaAlSi_3O_8.KAlSi_3O_8+MgCO_3+FeCO_3+5Al(OH)_3=$
$HKMgFeAl_2Si_3O_{12}+2NaH_2Al_3Si_3O_{12}+5H_2O+2CO_2-k.$

Supposing the sodium silicate is to the potassium silicate as 3 to 1, we have:

(5) $2(3NaAlSi_3O_8.KAlSi_3O_8)+2Fe_2O_3+8CaCO_3+2H_2O=$
$4HCa_2Al_2FeSi_3O_{13}+12SiO_2+K_2CO_3+3Na_2CO_3+4CO_2+k.$

The equations corresponding to (3) and (5) under orthoclase and microcline are not written, since their occurrence is very doubtful. The decrease in volume of the kaolinite and quartz as compared with the anorthoclase, equation (1), is 9.56 per cent, or of the kaolinite alone is 52.19 per cent. The decrease in volume of the gibbsite and quartz as compared with the anorthoclase, equation (2), is 3.30 per cent, or of the gibbsite alone is 68.02 per cent. The decrease in volume of the muscovite and paragonite, as compared with the anorthoclase and gibbsite, equation (3), is 20.04 per cent. The decrease in volume of the biotite and paragonite, as compared with the anorthoclase and gibbsite, equation (4), is 10.91 per cent. The decrease in volume of the epidote and quartz, as compared with the anorthoclase, hematite, and calcite, equation (5), is 28.30 per cent. Equations corresponding with the above and the volume relations can be easily worked out along analogous lines for other ratios of the sodium-bearing and potassium-bearing silicates, but the general results would be the same, so this is hardly worth the while.

The geological positions and physical conditions under which the

changes take place are identical with the corresponding changes of orthoclase and microcline—i. e., alterations represented by equations (1) and (2) take place in the zone of katamorphism, and especially the belt of weathering. Alterations (3) and (4) occur in the zone of anamorphism, and that of equation (5) is known for the belt of cementation. One general point is clear from the above, that in the anorthoclase rocks we have a source for paragonite in the paragonite-schists and paragonite-gneisses.

TRICLINIC.

The plagioclase feldspars are a group of triclinic feldspars which range from sodium-aluminum silicate to calcium-aluminum silicate. The former is a polysilicate and the latter an orthosilicate, hence there is great variation both as to composition and as to acidity. The names, compositions, and specific gravities of the species, as given by Tschermak and Dana, are as follows:

ALBITE, OLIGOCLASE, ANDESINE, LABRADORITE, BYTOWNITE, AND ANORTHITE.

Albite:
$NaAlSi_3O_8$.
Triclinic.
Sp. gr. 2.62–2.65.

Oligoclase:
Ab to Ab_3An_1.
Triclinic.
Sp. gr. 2.65–2.67.

Andesine:
Ab_3An_1 to Ab_1An_1.
Triclinic.
Sp. gr. 2.68–2.69.

Labradorite:
Ab_1An_1 to Ab_1An_3.
Triclinic.
Sp. gr. 2.70–2.72.

Bytownite:
Ab_1An_3 to An.
Triclinic.
Sp. gr. 2.72–2.74.

Anorthite:
$CaAl_2Si_2O_8$.
Triclinic.
Sp. gr. 2.74–2.76.

Occurrence.—The plagioclases are probably the most important rock-making constituents, being approached in abundance only by the orthoclase feldspars and by quartz. The plagioclases are present as pyrogenic constituents in the great majority of igneous rocks. They also occur very

abundantly as allogenic constituents in the sedimentary rocks. In such rocks the more siliceous plagioclases are more plentiful than the less siliceous plagioclases, because of the more ready decomposition of the latter. The plagioclases develop abundantly as autogenic constituents in the metamorphic rocks of both sedimentary and igneous origin. The plagioclase albite is recorded as being derived from analcite, heulandite, laumontite, plagioclases (with orthoclase), sodalite, spodumene, and stilbite. The plagioclase anorthite is not recorded as being derived from other minerals. But it is seen in the zone of katamorphism that anorthite passes into various zeolites by simple hydration. It can hardly be doubted that when such zeolites pass into the zone of anamorphism by dehydration they are sources of anorthite. Doubtless also anorthite is produced in different ways from the combinations of various minerals, just as it passes into different combinations of minerals. The intermediate feldspars, which are intermolecular mixtures of albite and anorthite, may be derived from any of the minerals from which albite and anorthite are formed.

Alterations.—In treating the alterations of the plagioclases the only practicable plan is to calculate equations and volume reactions separately for albite and for anorthite. For any of the intermediate feldspars the corresponding equations may be written by multiplying the albite and anorthite equations by the number of molecules of these compounds, respectively, and adding the products. However, the alterations of the plagioclases are so complicated that I have not been able to make the treatment more than very partial.

The species belonging to the more siliceous half of the plagioclase feldspars—i. e., albite, oligoclase, and andesine—frequently undergo alterations similar to those of the monoclinic feldspars, producing kaolin (monoclinic; sp. gr. 2.615), gibbsite (monoclinic; sp. gr. 2.35), and quartz (rhombohedral; sp. gr. 2.6535). These alterations may be considered as coming from the albite molecule.

But the more common alterations of the plagioclases are into the zeolites, epidote (monoclinic; sp. gr. 3.38), quartz, the scapolites, and paragonite (monoclinic; sp. gr. 2.84), and the less siliceous feldspars into more siliceous plagioclase feldspars. The plagioclases are also recorded as altering into prehnite (orthorhombic; sp. gr. 2.875) and albite. By pyrochemical methods plagioclase and sodium carbonate at 220° C. produce the zeolite analcite (isometric; sp. gr. 2.255), and this process is more rapid in propor-

tion as the feldspars are less siliceous. The alteration of a given feldspar may be into two or more of the above minerals. Doubtless often orthoclase and plagioclase together pass into other minerals. One such reaction has been considered by Becke, and is given below.

The less siliceous plagioclases, labradorite, bytownite, and anorthite, alter rarely to kaolin alone, but this mineral may separate simultaneously with zoisite (orthorhombic; sp. gr. 3.31) or epidote.

The alteration of albite to kaolin and quartz, to gibbsite and quartz, and of albite and gibbsite to paragonite, respectively, may be written as follows:

(1) $2NaAlSi_3O_8+2H_2O+CO_2=H_4Al_2Si_2O_9+4SiO_2+Na_2CO_3+k.$
(2) $2NaAlSi_3O_8+3H_2O+CO_2=2[Al(OH)_3]+6SiO_2+Na_2CO_3+k.$
(3) $NaAlSi_3O_8+2Al(OH)_3=NaH_2Al_3Si_3O_{12}+2H_2O+k.$

The decrease in volume in equation (1) of the kaolin and quartz is 4.89 per cent; in equation (2) the increase for the gibbsite and quartz is 1.58 per cent; in equation (3) the decrease for the paragonite, as compared with the albite and gibbsite, is 18.85 per cent.

Analcite (isometric; sp. gr. 2.22–2.29) may be derived from albite according to the following reaction:

(4) $2NaAlSi_3O_8+2H_2O=Na_2Al_2Si_4O_{12}.2H_2O+2SiO_2+k.$

The increase in volume is 20.82 per cent, supposing the silica separates as a solid.

Natrolite (orthorhombic; sp. gr. 2.20–2.25) may also be derived from albite according to the reaction:

(5) $2NaAlSi_3O_8+2H_2O=H_4Na_2Al_2Si_3O_{12}+3SiO_2+k.$

The increase in volume is 19.95 per cent, supposing the silica separates as a solid.

From anorthite a number of zeolites are derived. Clarke is one of the latest authors who has discussed the relations of the zeolites to the feldspars, and the chemical alterations given are obtained mainly from his paper.[a] The equations for the more common varieties may be written as follows:

Thomsonite (orthorhombic; sp. gr. 2.3–2.4) is derived from anorthite according to the following reaction:

(6) $3CaAl_2Si_2O_8+7H_2O=Ca_3Al_6Si_6O_{24}.7H_2O+k.$

The increase in volume is 34.65 per cent.

[a] Clarke, F. W., The constitution of the silicates: Bull. U. S. Geol. Survey No. 125, 1895, pp. 32–45.

Gismondite (monoclinic; sp. gr. 2.265) is derived from anorthite according to the following reaction:

(7) $3CaAl_2Si_2O_8+12H_2O=Ca_3Al_6Si_6O_{24}.12H_2O+k.$

The increase in volume is 52.76 per cent.

For laumontite (monoclinic; sp. gr. 2.305) the change does not appear to have been determined with reasonable certainty. It may be supposed to be derived from anorthite by the simultaneous union of freed calcium and aluminum with other compounds, the calcium perhaps passing into the carbonate and the aluminum into the hydrate. On this hypothesis the reaction is:

(8) $2CaAl_2Si_2O_8+7H_2O+CO_2=H_4CaAl_2Si_4O_{14}.2H_2O+CaCO_3+2[Al(OH)_3]+k.$

The increase in volume is 33.65 per cent, supposing the calcium carbonate to be dissolved and the aluminum hydroxide to remain as gibbsite. However, Clarke regards laumontite as derived from equal quantities of anorthite and the hypothetical compound trisilicic anorthite[a] ($Ca_3Al_6(Si_3O_8)_6$).

The zeolite phillipsite (monoclinic; sp. gr. 2.20) may be regarded as derived from albite, anorthite, and leucite, as follows:

(9) $6CaAl_2Si_2O_8+4NaAlSi_3O_8+6KAlSi_2O_6+48H_2O+2CO_2=$
$3(K_2Ca_2Al_6Si_{12}O_{36}.14H_2O)+2Na_2CO_3+4Al(OH)_3+k.$

The leucite is added as a source of the potassium. The increase in volume of the three compounds in passing into phillipsite is 31.98 per cent.

Heulandite (epistilbite) (monoclinic; sp. gr. 2.20) and stilbite (monoclinic; sp. gr. 2.1495) are regarded by Clarke as derived from the hypothetical compound trisilicic anorthite. Chabazite (rhombohedral; sp. gr. 2.12) is regarded by him as derived from this compound and from normal anorthite. All four, however, may be equally well considered as derived from intermediate plagioclases with carbonation of the excess of calcium and hydration of the excess of aluminum. On these hypotheses the reactions for the four may be written as follows:

(10) $4NaAlSi_3O_8+3CaAl_2Si_2O_8+21H_2O+2CO_2=$
$3(H_4CaAl_2Si_6O_{18}.3H_2O)+2Na_2CO_3+4[Al(OH)_3]+k.$

(11) $4NaAlSi_3O_8+3CaAl_2Si_2O_8+24H_2O+2CO_2=$
$Ca_3Al_6(Si_3O_8)_6.18H_2O+2Na_2CO_3+4Al(OH)_3+k.$

(12) $6NaAlSi_3O_8+6CaAl_2Si_2O_8+3CO_2+45H_2O=$
$2[Ca_3Al_6(SiO_4)_3(Si_3O_8)_3.18H_2O]+3Na_2CO_3+6[Al(OH)_3]+6SiO_2+k.$

[a] Clarke, F. W., The constitution of the silicates: Bull. U. S. Geol. Survey No. 125, 1895, p. 42.

Supposing the sodium carbonate is dissolved and the other compounds are solids, the increase in volume for (10) is 37.14 per cent, for (11) is 43.50 per cent, and for (12) is 46.76 per cent.

Scolecite (monoclinic; sp. gr. 2.16–2.40) may be derived from anorthite, according to the following reaction:

$$(13)\quad 3CaAl_2Si_2O_8+9H_2O+CO_2=2CaAl_2Si_3O_{10}.3H_2O+2Al(OH)_3+CaCO_3+k.$$

The increase in volume is 35.23 per cent, provided the gibbsite separates as a solid and the $CaCO_3$ is dissolved.

Mesolite (monoclinic or triclinic; sp. gr. 2.29), according to Clarke,[a] is an isomorphous mixture of equal quantities of natrolite and scolecite; therefore the reaction for this compound may be expressed by the following:

$$(14)\quad 4NaAlSi_3O_8+3CaAl_2Si_2O_8+13H_2O+CO_2= 2(H_8Na_2CaAl_4Si_6O_{24}.H_2O)+6SiO_2+2Al(OH)_3+CaCO_3+k.$$

The expansion in volume is 24.96 per cent, provided the silica and gibbsite separate as solids and the $CaCO_3$ is carried away in solution. If all products are solid the increase in the volume is 30.19 per cent.

Turning now from the zeolites to other minerals, the plagioclases are recorded as altering into prehnite (orthorhombic; sp. gr. 2.875). Since albite is recorded as simultaneously separating, the most probable reaction is by hydration of the anorthite molecule.

$$(15)\quad 4CaAl_2Si_2O_8+8H_2O=2H_2Ca_2Al_2Si_3O_{12}+4Al(OH)_3+2SiO_2+k.$$

Supposing the compounds formed to be solids, the increase in volume is 14.85 per cent.

Another important alteration of the plagioclases is into zoisite (orthorhombic; sp. gr. 3.25–3.37) or epidote (monoclinic; sp. gr. 3.25–3.5), with the simultaneous formation of kaolinite or gibbsite. The reaction for anorthite in the case of zoisite is probably:

$$(16)\quad 4CaAl_2Si_2O_8+3H_2O=H_2Ca_4Al_6Si_6O_{26}+H_4Al_2Si_2O_9+k,$$

or

$$(17)\quad 4CaAl_2Si_2O_8+4H_2O=H_2Ca_4Al_6Si_6O_{26}+2Al(OH)_3+2SiO_2+k.$$

The decrease in volume of the solids in (16) is 7.77 per cent, and in (17) is 4.58 per cent.

In the formation of epidote the reactions are of a similar kind, but Fe_2O_3 replaces some Al_2O_3 of the feldspar molecule. Supposing the

[a] Clarke, cit., Bull. 125, pp. 35–36.

aluminum is to the iron as 2 to 1, that the iron is derived from hematite, and that excess of aluminum separates as gibbsite, the reaction for anorthite is:

(18) $4CaAl_2Si_2O_8+Fe_2O_3+6H_2O=H_2Ca_4Al_4Fe_2Si_6O_{26}+H_4Al_2Si_2O_9+2Al(OH)_3+k,$

or

(19) $4CaAl_2Si_2O_8+7H_2O+Fe_2O_3=H_2Ca_4Al_4Fe_2Si_6O_{28}+4Al(OH)_3+2SiO_2+k.$

The increase of the volume of the epidote, kaolin, and gibbsite as compared with the anorthite and hematite, equation (18), is 3.6 per cent. The increase in volume of the epidote, gibbsite, and quartz as compared with the anorthite and hematite, equation (19), is 6.57 per cent.

The scapolites include marialite (tetragonal; sp. gr. 2.566), meionite (tetragonal; sp. gr. 2.70–2.74), and various isomorphous mixtures. (See pp. 311–312.) The alterations of the plagioclases into these two minerals are given. From these equations those for any definite isomorphous mixture of marialite and meionite can easily be formulated. According to Clarke,[a] albite changes into marialite, and anorthite into meionite. The reactions may be written as follows:

(20) $3NaAlSi_3O_8+NaCl=Na_4Al_3Si_9O_{24}Cl+k.$

Supposing the NaCl to be in solution, the increase in volume of the solid compound is 10.29 per cent. If the NaCl be supposed to be a solid, the increase in volume of the solid compound is 1.84 per cent. The change from anorthite to meionite is represented by the following reaction:

(21) $3CaAl_2Si_2O_8+CaCO_3=Ca_4Al_6Si_8O_{25}+CO_2+k.$

If the calcium carbonate be supposed to be present as a solid, the decrease in volume is 3.78 per cent; if it be supposed to be added in solution, the increase in volume is 7.87 per cent.

Becke records the alteration of orthoclase and plagioclase into albite (triclinic; sp. gr. 2.635), zoisite (orthorhombic; sp. gr. 3.31), muscovite (monoclinic; sp. gr. 2.88), and quartz (rhombohedral; sp. gr. 2.6535). His equation for this reaction is as follows:[b]

(22) $x(NaAlSi_3O_8)+4(CaAl_2Si_2O_8)+KAlSi_3O_8+2H_2O=$
$x(NaAlSi_3O_8)+2(HCa_2Al_3Si_3O_{13})+H_2KAl_3Si_3O_{12}+2SiO_2.$

It is impracticable at the present state of knowledge to write reactions representing the changes of the less siliceous plagioclases into more siliceous plagioclases and other minerals, because the exact compositions of the original and resultant minerals are not known. The alterations of the

[a] Clarke, F. W., The constitution of the silicates: Bull. U. S. Geol. Survey No. 125, 1895, p. 29.

[b] Becke, F., Ueber Beziehungen zwischen Dynamometamorphose und Molecularvolumen: Neues Jahrbuch für Mineralogie, etc., vol. 2, 1896, p. 182.

plagioclases to kaolinite, equation (1), and to gibbsite, equation (2), are by reactions of carbonation and hydration; the alterations to the zeolites, equations (4) to (14), inclusive, are by reactions of hydration, and (8) to (14), inclusive, also involve carbonation. The alteration to prehnite, equation (15), is a reaction of hydration and desilication. The alterations to zoisite and epidote, equations (16), (17), (18), and (19), are by reactions of hydration. All but (1), (3), (16), and (17) take place with increase of volume ranging from 1.58 to 52.76 per cent, provided all the compounds formed remain in situ. All take place with liberation of heat. The alterations in all particulars are characteristic of the zone of katamorphism.

The development of kaolin is probably more characteristic of the belt of weathering than of the belt of cementation. The development of the zeolites and epidotes is known to occur on an extensive scale in the belt of cementation, both within the bodies of other minerals and within the openings in rocks. Amygdules and veins of these minerals, with quartz, are of great importance in cementing rocks. The material for this work is doubtless in large part, though not altogether, derived from feldspathic minerals.

For the intermediate scapolites, equations (20) and (21), the alterations take place with a slight increase in volume for marialite and a slight decrease for meionite, provided all the compounds which enter into them are solids. The reactions are those of silication and decarbonation to some extent, and this involves absorption of heat. The geological occurrences correspond with the physical-chemical facts. The most common of the scapolites which occurs as a secondary product in the altered rocks is wernerite, an isomorphous mixture of meionite and marialite molecules. As stated by Dana, wernerite "occurs in metamorphic rocks, and most abundantly in granular limestone near its junction with the associated granitic or allied rock."[a] Wernerite is associated with such minerals as pyroxene, amphibole, and garnet, which occur as deep-seated alterations. The formation of wernerite from feldspar is probably, therefore, a deep-seated change which occurs in the zone of anamorphism.

The alteration of orthoclase and plagioclase together to albite, zoisite, muscovite, and quartz, equation (22), is a reaction of hydration and desilication. It involves an increase in volume. One would therefore expect the reaction to take place in the zone of katamorphism.

[a] Dana, J. D., A system of mineralogy; Descriptive mineralogy, by E. S. Dana; Wiley & Sons, New York, 6th ed., 1892, p. 470.

LEUCITE GROUP.

Leucite is the only rock-making mineral belonging to this group.

LEUCITE.

Leucite:
$KAlSi_2O_6$.
Isometric.
Sp. gr. 2.45–2.5.

Occurrence.—Leucite is a common constituent of volcanic rocks, especially the more recent ones. The fact that it is not abundant in the older volcanic rocks is probably due to its ready alteration. It may have been present originally.

Leucite is not known as a constituent of the schists and gneisses derived from the sediments. Leucite has been produced by pyro-chemical methods from analcite and potassium chloride. This is a reversal of the reaction in the case of change of leucite to analcite.

Alterations.—Leucite frequently alters to analcite (isometric; sp. gr. 2.22–2.29); to a mixture of orthoclase (monoclinic; sp. gr. 2.53–2.6) and kaolinite (monoclinic; sp. gr. 2.6–2.63); to a mixture of orthoclase and muscovite (monoclinic; sp. gr. 2.76–3.0); and to a mixture of orthoclase and nephelite (hexagonal; sp. gr. 2.55–2.65).

The change of leucite to analcite requires a substitution of sodium for potassium; hence sodium carbonate or some other sodium compound must be supposed to be present. Supposing sodium carbonate to be the compound, the reaction is:

(1) $2KAlSi_2O_6+Na_2CO_3+2H_2O=Na_2Al_2Si_4O_{12}.2H_2O+K_2CO_3+k.$

Ignoring the carbonates, the increase in volume is 10.74 per cent.

The passage of leucite into orthoclase and kaolin is as follows, supposing the freed potassium to unite with carbon dioxide:

(2) $4KAlSi_2O_6+CO_2+2H_2O=2KAlSi_3O_8+H_4Al_2Si_2O_9+K_2CO_3+k.$

Supposing the potassium carbonate to be taken into solution, the decrease in volume of the orthoclase as compared with the leucite is 38.57 per cent, and the decrease of the orthoclase and kaolinite together as compared with the leucite is 10.58 per cent.

In a similar way the passage of leucite into orthoclase and muscovite is as follows:

(3) $6KAlSi_2O_6+CO_2+H_2O=3KAlSi_3O_8+KH_2Al_3Si_3O_{12}+K_2CO_3+k.$

As before, supposing the potassium carbonate to be taken into solution, the decrease in volume of the orthoclase and muscovite as compared with the leucite is 12.43 per cent.

In the passage of leucite into orthoclase and nephelite it is necessary to suppose that a part of the potassium of the leucite is replaced by sodium. Supposing the nephelite formed to be a pure soda-nephelite, the reaction would be:

(4) $4KAlSi_2O_6+Na_2CO_3=2KAlSi_3O_8+2NaAlSiO_4+K_2CO_3+k.$

Ignoring the carbonates, the decrease in volume of the orthoclase and nephelite as compared with the leucite is 7.59 per cent.

The reactions above given, except the last, are those of hydration, and the second and third are those of carbonation also. They are, therefore, reactions which are to be expected in the zone of katamorphism. The change of leucite into orthoclase and nephelite gives decrease in volume, with neither hydration nor dehydration, carbonation nor silication. It is, therefore, to be expected that the change is one which takes place in the zone of anamorphism.

The artificial transformation of leucite into analcite by treatment with soda solutions, and the reverse alteration of analcite into leucite by treatment with potassium solutions, as shown by Lemberg,[a] is an excellent illustration of the law of mass action and proves the importance of this principle under natural conditions.

PYROXENE GROUP.

ORTHORHOMBIC PYROXENES.

ENSTATITE, BRONZITE, AND HYPERSTHENE.

Enstatite:
$MgSiO_3$.
Orthorhombic.
Sp. gr. 3.1–3.3.

Bronzite:
$(MgFe)SiO_3$ where Mg : Fe : : 8:1, 6:1, and 3:1.
Orthorhombic.
Sp. gr. 3.2–3.3.

Hypersthene:
$(MgFe)SiO_3$ where Mg : Fe : : 3:1, nearly to 1:1.
Orthorhombic.
Sp. gr. 3.4–3.5.

[a] Lemberg, J., Ueber Silicatumwandlungen: Zeitschr. Deutsch. geol. Gesell., vol. 28, 1876, pp. 536–545.

Occurrence.—The rhombic pyroxenes are common pyrogenic constituents of igneous rocks rich in magnesium. They are common in the normal diabases, gabbros, and basalts, and are abundant in the norites, peridotites, etc. They also occur in the intermediate, basic, and ultrabasic volcanic rocks, including both lavas and tuffs. A very common associate of the rhombic pyroxenes is olivine. The rhombic pyroxenes also occur in the schists and gneisses, especially those derived from eruptives. In such rocks they are frequently associated with the monoclinic pyroxenes. They further occur as vein materials and are found in meteorites.

As metamorphic minerals, enstatite is derived from pyrope and hypersthene from almandite, biotite, and common garnet.

Alterations.—The most frequent alteration of the rhombic pyroxenes is to talc (orthorhombic or monoclinic; sp. gr. 2.7–2.8). The less frequent alterations are to serpentine (monoclinic; sp. gr. 2.50–2.65), bastite (orthorhombic; sp. gr. 2.50–2.75), actinolite (monoclinic; sp. gr. 3–3.2), and anthophyllite (orthorhombic; sp. gr. 3.1–3.2).

For the sake of simplicity it is assumed that where pure talc or serpentine is produced these materials are derived from enstatite; and that where bastite, actinolite, and anthophyllite are produced these minerals are derived from bronzite or hypersthene. Of course, serpentine or talc may be produced from bronzite or hypersthene, the iron separating as oxide or carbonate. One such possible alteration is written. However, the ordinary alterations of the ferriferous pyroxenes are to bastite, which is iron-bearing.

The change of enstatite to talc is as follows:

(1) $4MgSiO_3+CO_2+H_2O=H_2Mg_3Si_4O_{12}+MgCO_3+k.$

Supposing the magnesium carbonate to be dissolved, the increase in volume is 9.93 per cent. If a ferriferous pyroxene be supposed to alter to talc, iron oxide must separate. Supposing this to be in the form of magnetite (isometric; sp. gr. 5.174), and supposing that the magnesium is to the iron as 3:1, or that the mineral is intermediate between bronzite and hypersthene, the reaction may be written:

(2) $3Mg_3FeSi_4O_{12}+3H_2O+O=3H_2Mg_3Si_4O_{12}+Fe_3O_4+k.$

Similar equations may be written by which, instead of magnetite, hematite (rhombohedral; sp. gr. 5.225) or limonite (amorphous; sp. gr. 3.80) is produced, in which case the expansion of volume would be

greater. The calculated increase in volume of the talc and magnetite, as compared with the pyroxene, is 14.68 per cent, provided the average specific gravity of bronzite be used, and 21.73 per cent provided the average specific gravity of hypersthene be used. Probably the real increase in volume is the average of the above, or about 18.20 per cent.

In the case of a hypersthene in which the iron is to the magnesium as 1:1 the alteration to talc may be as follows, provided the iron separate as magnetite:

(3) $3MgFeSi_2O_6+H_2O+O=H_2Mg_3Si_4O_{12}+Fe_3O_4+2SiO_2+k.$

The increase of volume of the talc, magnetite, and quartz as compared with the hypersthene is 12.84 per cent.

Serpentine is produced from enstatite by the following reaction:

(4) $3MgSiO_3+2H_2O=H_4Mg_3Si_2O_9+SiO_2+k.$

In case the SiO_2 is dissolved, the increase in volume is 14.25 per cent; if it separates as quartz (rhombohedral; sp. gr. 2.6535) the increase in volume is 38.36 per cent.

If a rhombic pyroxene be taken in which the magnesium is to the iron as 3:1—i. e., stands on the border line between hypersthene and bronzite—serpentine might be produced by the following reaction, with the simultaneous separation of hematite and quartz:

(5) $2Mg_3FeSi_4O_{12}+4H_2O+O=2H_4Mg_3Si_2O_9+Fe_2O_3+4SiO_2+k.$

Using the specific gravity of hypersthene, in case only serpentine and hematite separate as solids, the decrease in volume is 2 21 per cent, and if the silica separates as quartz the increase of volume is 33.94 per cent.

Supposing the calcium is to the iron as 1:1 and the excess of iron separates as magnetite, the reaction is:

(6) $3MgFeSi_2O_6+2H_2O+O=H_4Mg_3Si_2O_9+Fe_3O_4+4SiO_2+k.$

The increase in volume of the serpentine, magnetite, and quartz as compared with the hypersthene is 20.24 per cent.

Other reactions may be written which represent the alterations of bronzites and hypersthenes, in which the proportions of magnesium and iron are different. Also reactions may be written in which the oxide of iron forms as magnetite or limonite. Where magnetite forms, the increase in volume would be less than for hematite, and where limonite forms the increase in volume would be considerably greater.

If in the formation of bastite, a pyroxene be taken which stands intermediate between bronzite and hypersthene—i. e., in which the magnesium and iron are as 3:1—and if the same proportions of these constituents be supposed to hold in the bastite, the reaction is as follows:

(7) $3Mg_3FeSi_4O_{12}+8H_2O=H_{16}Mg_9Fe_3Si_8O_{36}+4SiO_2+k.$

Using the specific gravity of hypersthene, if the silica be dissolved the increase of volume is 22.77 per cent (if the specific gravity of bronzite be employed, 15.65 per cent); if the silica separates as quartz, 46.87 per cent. Similar reactions may be written which represent the formation of bastites which are richer and poorer in iron, in which cases the volume changes are slightly different.

The passage of ferriferous rhombic pyroxene into anthophyllite may be one of pure paramorphism, since in anthophyllite the proportions of magnesium to iron have ranges paralleled by bronzite and hypersthene. Therefore, the only necessary change is a molecular one, a mineral being produced of lower symmetry and lower specific gravity as a result of the alteration. If the specific gravity of hypersthene be used, the calculated increase in volume due to the lower specific gravity of the resultant mineral is 8.70 per cent.

In the formation of actinolite from a rhombic pyroxene, it is necessary that lime and silica be added. Supposing the magnesium is to the iron as 3:1 in both the rhombic pyroxene and actinolite, the equation is as follows:

(8) $3Mg_3FeSi_4O_{12}+4CaCO_3+4SiO_2=Mg_9Fe_3Ca_4Si_{16}O_{48}+4CO_2+k.$

The decrease in volume of the actinolite as compared with pyroxene, calcite, and quartz is 7.40 per cent if the specific gravity of hypersthene be used, and if that of bronzite is 10.77 per cent. Similar equations may be written in which the proportions of magnesium and iron are different.

The changes of the rhombic pyroxenes to talc involve reactions of carbonation and hydration, or of hydration and oxidation, or of all three together. The changes of the rhombic pyroxenes to serpentine and bastite involve hydration alone, or hydration and oxidation. All take place with increase of volume and liberation of heat.

Corresponding with these facts, as a matter of observation the development of serpentine, bastite, and talc from the rhombic pyroxenes takes place in the zone of katamorphism. The development of talc is especially characteristic of the belt of weathering, and serpentine and bastite of the

belt of cementation, although it can not be asserted that the formation of any of these minerals is confined to either belt.

The paramorphic change of rhombic pyroxene into anthophyllite being one involving lessening of specific gravity and decrease of symmetry, one would expect the change to take place in the upper physical-chemical zone, but I have been unable to ascertain from the literature the facts in this case.

The formation of actinolite from a rhombic pyroxene requires the assistance of calcite and silica. This reaction is one of silication and decarbonation. It occurs with diminution of volume and absorption of heat. As a matter of observation, corresponding with these facts it is well known that the change is a deep-seated one.

MONOCLINIC PYROXENES.

DIOPSIDE, SAHLITE, HEDENBERGITE, AUGITE, ACMITE, SPODUMENE, WOLLASTONITE, AND PECTOLITE.

Diopside:
$CaMgSi_2O_6$.
Monoclinic.
Sp. gr. 3.2–3.38.

Sahlite:
$Ca(MgFe)Si_2O_6$.
Monoclinic.
Sp. gr. 3.25–3.4.

Hedenbergite:
$CaFeSi_2O_6$.
Monoclinic.
Sp. gr. 3.5–3.58.

Augite:
$Ca(MgFe)Si_2O_6$ with $(MgFe)\ (AlFe)_2SiO_6$.
Monoclinic.
Sp. gr. 3.3–3.5.

Acmite:
$NaFeSi_2O_6$.
Monoclinic.
Sp. gr. 3.50–3.55.

Spodumene:
$LiAlSi_2O_6$.
Monoclinic.
Sp. gr. 3.13–3.20.

Wollastonite:
$CaSiO_3$.
Monoclinic.
Sp. gr. 2.8–2.9.

Pectolite:
$HNaCa_2Si_3O_9$.
Monoclinic.
Sp. gr. 2.68–2.78.

The minerals diopside, sahlite, and augite constitute the so-called diopside-augite series.

Occurrence.—The pyroxene group is one of the most widespread and important. One or another variety of pyroxene may occur in almost any rock; but the pyroxenes are much more abundant in the intermediate and basic than in the acidic rocks. Pyroxene is found in the plutonic and volcanic rocks, as an original constituent of the clastic rocks, and as an original and secondary constituent of the metamorphosed rocks, both of igneous and of aqueous origin. The minerals of the pyroxene group occur extensively in veins.

Diopside occurs in marbles, especially magnesian marbles. Indeed, this is the common form of pyroxene which develops as a secondary constituent during the metamorphism of the magnesian limestones. It also occurs in veins. As a metamorphic mineral diopside is derived from dolomite.

Sahlite occurs in ferriferous magnesian marbles. Like diopside, it is also found in veins. Unlike diopside, it is a common product in many hornblendic schists and gneisses, such rocks probably having been in their original condition calcareous, magnesian, and ferriferous. Sahlite is derived from ankerite and parankerite.

Hedenbergite occurs as a rather common constituent of some nepheline syenites and other basic syenites.

Augite is a common form of pyroxene in the eruptive rocks, both plutonic and volcanic. It occurs in many mechanical sediments. It also is found in metamorphic rocks of both igneous and sedimentary origin, though in the sedimentary metamorphosed rocks it is less common than diopside and sahlite. But augite develops to a considerable extent in the sedimentary rocks which are intermediate between the chemical and mechanical rocks—that is, those which contain abundant calcium carbonate and also are rich in aluminum. Augite is recorded as a metamorphic mineral derived from hornblende.

Wollastonite occurs especially in the metamorphosed calcareous and sedimentary rocks, it being a secondary product produced by metamorphism. It is found abundantly in marbles, and in schists and gneisses which were originally calcareous, especially the calcareous feldspathic schists. It also develops in calcareous inclusions in eruptive rocks, and is found as a contact

product of igneous and calcareous rocks. The schists and gneisses containing wollastonite are often garnetiferous and epidotic.

The very frequent development of the above pyroxenes in the sedimentary rocks which are calcareous, rather than amphiboles, is due to the fact that the pyroxenes are richer in calcium than are the amphiboles. Where sedimentary rocks contain magnesium abundantly with the calcium, the amphiboles are likely to form rather than the pyroxenes.

Acmite occurs mainly in the eruptive rocks, and especially in those which are rich in alkalies. According to Rosenbusch, it occurs especially in granites and syenites rich in sodium, in the elæolite-syenites, phonolites, and leucitophyres. As a metamorphic mineral acmite is derived from arfvedsonite.

Spodumene sometimes occurs as an accessory constituent in the granites, schists, and gneisses, and in some cases as considerable masses.

Pectolite, while not an abundant mineral, is present as a secondary constituent in many basic eruptive rocks, both plutonic and volcanic. It is, however, especially prevalent in the volcanic rocks, since these are more porous, and pectolite is especially likely to occur in cavities or seams. Occasionally pectolite is found in the metamorphic rocks as a product of apophyllite.

Alterations of the diopside-augite series.—The most common alteration of the non-aluminous diopside and sahlite is into talc (orthorhombic or monoclinic; sp. gr. 2.7–2.8). They also often alter into serpentine (monoclinic; sp. gr. 2.5–2.65). These changes are accompanied by the formation of calcium carbonate, and frequently by the separation of a part of this carbonate as calcite (rhombohedral; sp. gr. 2.7135).

The aluminous pyroxenes, augite, and diallage, under the conditions of the zone of katamorphism, change into chlorite (monoclinic; sp. gr. 2.08–2.16), with which are usually associated epidote (monoclinic; sp. gr. 3.25–3.5), this mineral often being embedded in the chlorite and calcite. Under conditions of weathering, any of the minerals of the diopside-augite series may be partly or entirely replaced by quartz (rhombohedral; sp. gr. 2.6535), chalcedony (cryptocrystalline; sp. gr. 2.6–2.64), or calcite. Such replacements are particularly common in the case of the porous andesites and trachytes, and also in tuffs. Not infrequently this replacement of the pyroxene occurs without the feldspar being greatly affected.

However, perhaps the most frequent and characteristic of the alterations of the diopside-augite series is uralitization or change to amphibole (monoclinic; sp. gr. 2.9–3.4). This process is particularly characteristic of the ancient igneous rocks, and especially those which are under comparatively deep-seated conditions, although the alteration is by no means confined to deep-seated rocks. It occurs on a great scale under the conditions of the transformation of the igneous rocks into schists and gneisses. During the process of uralitization epidote also very frequently forms. Not infrequently also magnetite (isometric; sp. gr. 5.16–5.18) and calcite separate. In some cases the change is accompanied by the development of a feldspar, such as albite (triclinic; sp. gr. 2.62–2.65). The kind of amphibole which forms depends upon the variety of the pyroxene. From diopside, tremolite (monoclinic; sp. gr. 2 9–3.1) is the ordinary product; from sahlite, actinolite (monoclinic; sp. gr. 3.0–3.2) is normally to be expected; from diallage and omphacite (according to Zirkel,[a] varieties of augite), smaragdite (a variety of hornblende) is ordinarily produced; and from ordinary augite, hornblende (monoclinic; sp. gr. 3.05–3.47) is usually developed. Finally, it not infrequently occurs that augite changes directly into biotite (monoclinic; sp. gr. 2.90).

The change of diopside to talc may be written as follows:

(1) $3CaMgSi_2O_6+3CO_2+H_2O=H_2Mg_3Si_4O_{12}+3CaCO_3+2SiO_2+k.$

The increase in volume, supposing all compounds remain as solids, is 48.74 per cent. If only the talc remains, the decrease is 30.13 per cent. Supposing the diopside were one in which a part of the calcium and magnesium were replaceable by iron, so that the calcium and magnesium and iron are present in equal proportion, thus approaching sahlite in composition, and supposing the iron to pass into magnetite, the reaction is—

(2) $3CaMgFeSi_2O_9+3CO_2+H_2O+O=H_2Mg_3Si_4O_{12}+3CaCO_3+Fe_3O_4+5SiO_2+k.$

The increase in volume of the talc, calcite, magnetite, and quartz, as compared with the diopside, is 27.88 per cent.

The change of diopside to serpentine may be represented by the following equation:

(3) $3CaMgSi_2O_6+3CO_2+2H_2O=H_4Mg_3Si_2O_9+4SiO_2+3CaCO_3+k.$

[a] Naumann, C. F., and Zirkel, F., Elemente der Mineralogie, Leipzig, 1898, p. 696.

Supposing all the compounds separated as solids, the increase in volume is 56.32 per cent. If only the serpentine and quartz remain as solids, the increase in volume is 0.44 per cent.

The change from sahlite to ferriferous bastite, provided that in both compounds the magnesium is to the iron as 3 : 1, is—

$$(4)\quad 3Ca_4Mg_3FeSi_8O_{24}+12CO_2+8H_2O=H_{16}Mg_9Fe_3Si_8O_{36}+16SiO_2+12CaCO_3+k.$$

If all the compounds separate as solids, the increase in volume is 56.41 per cent; if the bastite and quartz remain as solids, 1.93 per cent. Supposing the calcium, magnesium, and iron were in equal proportions in the sahlite, and that in the bastite the magnesium were to the iron as 3 : 1, the equation may be written—

$$(5)\quad 9CaMgFeSi_3O_9+9CO_2+8H_2O+2O=H_{16}Mg_9Fe_3Si_8O_{36}+2Fe_3O_4+9CaCO_3+19SiO_2+k.$$

The increase in volume of the serpentine, magnetite, calcite, and quartz, as compared with the sahlite, is 37.50 per cent.

It is, of course, not impossible that serpentine shall develop as one of the products from augite. In this case it doubtless forms from the sahlite molecule of the augite compound, the sesquioxide compounds passing into some other mineral. It hardly seems advisable to attempt to write equations representing such an alteration.

In writing equations for the alterations of the aluminous pyroxenes into chlorite and epidote it is necessary that certain assumptions shall be made in reference to the relative proportions of the various elements. Moreover, if equations are written which produce chlorite alone, a large amount of the sesquioxide bases must be left over. If an equation be written for the formation of epidote, a large amount of magnesium is unaccounted for. Since it is very common for the minerals chlorite and epidote to form simultaneously, an equation is written on this supposition. In order to give definiteness to the compound, it is supposed that there are twice as many molecules of the diopside part of the augite molecule as of the other part. Furthermore, it is supposed for the diopside molecule that the magnesium is to the iron as 2:1; and for the other molecule that the aluminum is to the iron sesquioxide as 3:1. An epidote is taken in which the aluminum is to the iron as 2:1. A chlorite between clinochlore and prochlorite is taken, as such a chlorite is at about the middle of the series. As may be seen by reference to the analyses of augites and epidotes, the proportions taken represent about their

average compositions. With all these hypotheses, and supposing the extra silica to separate as quartz, the magnesia to separate as magnesium carbonate, and the iron as sesquioxide of iron, the equation may be written as follows:

$$(6)\quad 6[2(Ca_3Mg_2FeSi_6O_{18}).Mg_4Fe_2Al_2Fe_3Si_6O_{36}]+12CO_2+39H_2O+12O=$$
$$18(HCa_2Al_2FeSi_3O_{13})+3(H_{20}Mg_{12}Al_6Si_7O_{45})+33SiO_2+12Fe_2O_3+12MgCO_3+k.$$

If all the compounds remain as solids the increase in volume is 15.43 per cent. If the magnesium carbonate be dissolved the increase in volume is 8.58 per cent.

It is evident that many other equations could be written if other suppositions be made as to the relative proportions of the magnesium to the iron and the aluminum to the iron in the respective compounds, and if other chlorites than the particular one chosen be produced. For the complex silicates, present knowledge is not sufficient to determine whether or not particular equations written accurately represent the alterations which take place, although closer study in the future may possibly determine this. But there is little doubt that substantially the change represented by equation (6) has occurred in many instances, whether it can be verified in an individual case or not, as doubtless have also a multitude of alterations which might be represented by other possible equations. The difficulty is to ascertain in a given instance which of the equations represents a given alteration. It is hoped that the quantitative statement of the problem given by equation (6) and following equations will lead to closer study of the compounds which enter into new compounds and the compounds which are produced, and thus to more exact knowledge of the various alterations of augite.

According to the above reactions, as would be expected from the nature of the compounds, the alteration of diopside and sahlite more frequently produces talc, serpentine, and bastite, while the alteration of augite more frequently produces chlorite and epidote.

As already noted, perhaps the most characteristic of the alterations of the pyroxenes is to the amphiboles. This alteration involves the substitution of magnesium, or magnesium and iron, for calcium. It is supposed that the iron and magnesium are added in the form of carbonate, and that the liberated calcium separates in the form of carbonate. Parallel equations can, however, readily be written on the basis of any other magnesium compound being added and similar iron and calcium compounds being

produced. It is assumed, further, that the alteration of a pyroxene results in the production of the most closely allied amphibole. Of course this is not always the fact, but it is believed to be usual. Following this assumption, the alteration of diopside is to tremolite, of sahlite is to actinolite, of augite is to hornblende.

The change from diopside to tremolite may be written as follows:

(7) $2CaMgSi_2O_6+MgCO_3=CaMg_3Si_4O_{12}+CaCO_3+k.$

Regarding the magnesium carbonates as added in solution and the calcium carbonate as subtracted in solution, the increase in volume is 5.68 per cent. If the magnesium carbonate be considered as present as magnesite, and the calcium carbonate be considered as present as calcite, the increase in volume is 10.55 per cent.

The change from sahlite to actinolite, supposing the magnesium and iron to be present in the sahlite in equal proportions, is as follows:

(8) $2Ca_2MgFeSi_4O_{12}+FeCO_3+MgCO_3=Ca_2Mg_3Fe_3Si_8O_{24}+2CaCO_3+k.$

Supposing the sahlite and actinolite only to be solids, the increase in volume is 7.28 per cent. If all the compounds are regarded as solids on both sides of the equation, the increase in volume is 10.81 per cent.

Supposing that in the augite compound there are two of the sahlite molecules to one of the sesquioxide molecule, and supposing that the magnesium and iron are in equal proportions in both the augite and hornblende, the general alteration may be written as follows:

(9) $2[Ca_2MgFeSi_4O_{12}.(MgFe)(AlFe)_2SiO_6]+FeCO_3+MgCO_3=$
$Ca_2Mg_3Fe_3Si_8O_{24}.(MgFe)_2(AlFe)_4Si_2O_{12}+2CaCO_3+k.$

But before the volume relations can be calculated it is necessary to assume definite proportions between Mg and Fe, and Al and Fe, in the second members of the augite and hornblende molecules. If the magnesium be taken to the iron as 2:1 and the aluminum to the iron as 2:1, an average case, and only the augite and hornblende be considered as solids, the increase in volume is 4.30 per cent. If all the compounds in both equations are solids, the increase in volume is 6.14 per cent.

An inspection of the above equations giving the alterations of the diopside-augite series to amphibole shows that the chemical change in the alteration of diopside and sahlite to tremolite and actinolite is relatively greater than in the alteration of augite to hornblende. Moreover, if it be

supposed that the last half of the augite and hornblende molecules are present in greater proportion than given in the equations, the chemical change would be of still less relative importance. This is of interest because the alteration of augite to hornblende is a far more common phenomenon than the alterations of diopside and sahlite to tremolite and actinolite The equations also give reasons for the very frequent occurrence of calcite with uralite. The nature of the alterations is such that calcium carbonate must be produced, and very naturally a portion of this substance frequently separates as calcite.

In the change of augite to biotite it is necessary that potassium be derived from some source. Supposing it to be furnished in the form of potassium carbonate, as a result of the decomposition of some of the potassium-bearing silicates, the simplest form of reaction may be written as follows:

(10) $2[Ca(MgFe)Si_2O_6.(MgFe)(AlFe)_2SiO_6]+K_2CO_3+H_2O+CO_2=$
$2HK(MgFe)_2(AlFe)_2Si_3O_{12}+2CaCO_3+k.$

Supposing the MgO: FeO:: 2: 1, and the Al_2O_3: Fe_2O_3:: 3: 1—these ratios being chosen because they represent about an average of the analyses—and multiplying the above equation by 6, we have:

(11) $2[Ca_6Mg_4Fe_2Si_{12}O_{36}.Mg_4Fe_2Al_2Fe_2Si_6O_{36}]+6K_2CO_3+6H_2O+6CO_2=$
$2(H_6K_6Mg_8Fe_4Al_2Fe_2Si_{18}O_{72})+12CaCO_3+k.$

Disregarding all other compounds, the increase in volume of the biotite as compared with the augite is 17.26 per cent.

The alteration of diopside and sahlite to talc, serpentine, and bastite, equations (1), (3), and (4), all involve increase in volume and liberation of heat; also they are alterations involving carbonation and hydration. Equations (2) and (5) involve carbonation, hydration, and oxidation. In all except equation (1), even if all of the separated quartz and calcite is dissolved, there is still an increase in volume. They therefore stand as alterations that are typical of all the principles of metamorphism in the zone of katamorphism.

The changes of the pyroxenes, especially augite, to chlorite and epidote, equation (6), involve hydration, carbonation, and oxidation. The change occurs with increase in volume and liberation of heat, even if the resultant oxide of iron and magnesium carbonate be ignored. If these separate as solids, the increase in volume is considerable. The alteration is, therefore,

like the change to talc, serpentine, and bastite, one characteristic of the upper physical-chemical zone. The change of pyroxene to the fibrous amphibole known as uralite occurs in the belt of cementation on an extensive scale, and to this position the volume change corresponds.

But the passage of pyroxene into definite amphibole individuals is one of the most common alterations in the zone of anamorphism, and especially under conditions of mashing. The rule for this zone is for alterations to occur which result in minerals of higher specific gravity. The alteration of pyroxene to amphibole seems to be an exception to this rule; for the specific gravity of the pyroxenes ranges between 3.2 and 3.6, while that of the amphiboles varies from 2.9 to 3.4.

Mainly in consequence of this decrease in specific gravity the increase in volume, as already seen, of all compounds entering into the reactions in the change from diopside to tremolite, equation (7), is 10.55 per cent; of sahlite to actinolite, equation (8), 10.81 per cent; of augite to hornblende, equation (9), 6.14 per cent, supposing that the necessary chemical constituents added to the pyroxene are solid carbonates and the other compounds produced are solid carbonates.

Unlike the previous alterations, these changes do not involve oxidation, hydration, or carbonation; nor, on the other hand, do they involve deoxidation, dehydration, or silication. They are substitution reactions, by which magnesium, or iron, or both take the place of calcium. They are, therefore, analogous to the dolomitization or ferritization of the limestones; but the volume change is in an opposite sense from those alterations.

But another factor may enter into the problem, the effect of which is hard to estimate. The exchange of the magnesium and iron for calcium is supposed to take place with the separation of a carbonate. If such carbonate were simultaneously silicated, the entire volume change for all the factors concerned would be decrease. It is necessary to consider the volume relations of all the resultant minerals rather than those of the pyroxene and amphibole alone, and hence it may be that in the change of pyroxene to amphibole in the lower physical-chemical zone, if one could ascertain the entire effect of this alteration in connection with other alterations, the volume would not be expanded but contracted, and thus there be no real exception to the law that the reactions here take place with condensation of volume.

But, even if this be true, it is freely admitted that the case is not fully covered, for it is very uncommon indeed for the chief resultant mineral of an alteration in the zone of anamorphism to have a lower specific gravity than the minerals from which it is derived with comparatively small chemical change. Apparently, for some reason the amphiboles are more stable under conditions of moderately deep-seated metamorphism than the pyroxenes. This view is confirmed by the fact that, while the majority of the schists and gneisses are amphibolitic rather than pyroxenitic, in some of the gneisses and schists which have been altered under very deep-seated conditions the pyroxenes are present instead of the amphiboles. The significance of this fact is probably that an unusually high pressure is required in order to produce the mineral of the highest specific gravity in the case of the pyroxene-amphibole group.

The change from augite to biotite, equations (10) and (11), is one which takes place in the zone of anamorphism especially under conditions of mashing. In this change the volume of the biotite produced is greater than that of the pyroxene; in the case of the equation (11) 17.26 per cent. However, this case is similar to that of hornblende. Potassium salt must be added from some other mineral and a calcium salt is produced. In order to get the real volume relation of the reaction it would be necessary to know the source of the potassium and the place to which the calcium goes; and as present information does not enable us to determine this, no definite statement can be made as to the total effect of all the changes involved in the alteration of augite to biotite.

Alterations of pyroxenes other than the diopside-augite series.—No equations are written for the alterations of wollastonite, hedenbergite, acmite, and pectolite, because the character of the alterations of these compounds has not been described in the standard authorities, although there is no doubt that these minerals, like all others, do undergo various alterations. All these minerals form under deep-seated conditions; and it is to be expected that under the conditions of the zone of katamorphism, especially in the belt of weathering, they would be decomposed; but, if so, the minerals into which they change are unknown.

Alterations of spodumene are recorded. According to Dana, the first stage in the alteration of spodumene is to beta-spodumene (crystallization not determined; sp. gr. 2.644–2.649), in which one-half of the lithium is

replaced by sodium. The second stage in the process of alteration is the beta-spodumene passing into eucryptite (hexagonal; sp. gr. 2.667) and albite (triclinic; sp. gr. 2.62–2.65), or into muscovite (monoclinic; sp. gr. 2.76–3) and albite, the uniform mixture of which has been known as cymatolite (sp. gr. 2.69–2.70); or spodumene may pass into muscovite and microcline (triclinic; sp. gr. 2.54–2.57). The reactions representing the above changes may be expressed in the manner shown by the equations given below.

The change from spodumene to beta-spodumene may be written:

(12) $4LiAlSi_2O_6+Na_2CO_3=2LiNaAl_2Si_4O_{12}+Li_2CO_3+k.$

The increase in volume is 24.72 per cent. Where the beta-spodumene breaks up into eucryptite and albite the reaction is:

(13) $LiNaAl_2Si_4O_{12}=LiAlSiO_4+NaAlSi_3O_8+k.$

The increase in volume is 0.05 per cent. Where the beta-spodumene passes into muscovite and albite the reaction is:

(14) $6LiNaAl_2Si_4O_{12}+K_2CO_3+2H_2O+2CO_2=2H_2KAl_3Si_3O_{12}+6NaAlSi_3O_8+3Li_2CO_3+k.$

The decrease in volume is 0.76 per cent. In case the spodumene changes into muscovite and microcline the reaction is:

(15) $12LiAlSi_2O_6+4K_2CO_3+2CO_2+2H_2O=2H_2KAl_3Si_3O_{12}+6KAlSi_3O_8+6Li_2CO_3+k.$

The increase in volume is 31.74 per cent.

One would expect reactions (12) and (15) to take place in the zone of katamorphism, but I know of no observations on this point, nor as to the conditions under which reactions (13) and (14) occur.

AMPHIBOLE GROUP.

ORTHORHOMBIC AMPHIBOLES.

ANTHOPHYLLITE AND GEDRITE.

Anthophyllite:
$(MgFe)SiO_3$ Mg:Fe::4:1, 3:1, etc.
Orthorhombic.
Sp. gr. 3.1–3.2.

Gedrite:
$(MgFe)_2Si_2O_6.MgAl_2SiO_6$.
Orthorhombic.
Sp. gr. 3.1–3.2.

Occurrence.—Anthophyllite and gedrite occur in the schists and gneisses, both those derived from sedimentary and those derived from igneous rocks.

They are frequently associated with hornblende and mica. Anthophyllite occupies the same position in the rhombic amphiboles that bronzite does in the rhombic pyroxenes, and gedrite the same position as hypersthene. As already described (p. 270), the bronzites and hypersthenes alter into anthophyllite. It is to be expected that gedrite in a similar manner forms from hypersthene, but this particular alteration is not mentioned in the standard books of reference. Also, as described (p. 310), anthophyllite forms as a secondary product from olivine.

Alterations.—Anthophyllite by hydration passes into talc (orthorhombic or monoclinic; sp. gr. 2.75) or bastite (orthorhombic; sp. gr. 2.6). Also, Lacroix states[a] that rarely it alters into calcite (rhombohedral; sp. gr. 2.7135). Supposing the magnesium is to the iron as 3:1, and that the freed iron separates as hematite (rhombohedral; sp. gr. 5.225), the alteration to talc may be written as follows:

(1) $2Mg_3FeSi_4O_{12}+2H_2O+O=2H_2Mg_3Si_4O_{12}+Fe_2O_3+k.$

The increase in volume of the talc and hematite, as compared with the anthophyllite, is 11.41 per cent. If the iron oxide be supposed to be hydrated into limonite (not crystallized; sp. gr. 3.80), the increase in volume would be still greater. If bastite be produced, and it be supposed that the magnesium is to the iron as 3:1, the same as in the anthophyllite, the equation may be written:

(2) $3Mg_3FeSi_4O_{12}+8H_2O=H_{16}Mg_9Fe_3Si_8O_{36}+4SiO_2+k.$

The increase in volume of the bastite and quartz (rhombohedral; sp. gr. 2.6535) as compared with the anthophyllite is 34.09 per cent. If the silica be supposed to be dissolved the increase in volume is 12.09 per cent.

The particular alterations which gedrite undergoes are not described in the standard text-books; therefore no attempt is made to write equations for changes of this mineral.

The alteration of anthophyllite to talc and iron oxide involves hydration and oxidation. The alteration of anthophyllite to bastite involves hydration and desilication. Both sets of reactions are, therefore, characteristic of the zone of katamorphism; and it is in this zone, especially in the belt of weathering, that the changes occur.

[a] Lacroix, A., Minéralogie de la France, Paris, 1893–95, vol. 1, p. 637.

MONOCLINIC AMPHIBOLES.

The monoclinic amphiboles include the following rock-making minerals:

TREMOLITE, ACTINOLITE, CUMMINGTONITE, GRÜNERITE, HORNBLENDE, GLAUCOPHANE, RIEBECKITE, AND ARFVEDSONITE.

Tremolite:
$CaMg_3Si_4O_{12}$
Monoclinic.
Sp. gr. 2.9–3.1.

Actinolite:
$Ca(MgFe)_3Si_4O_{12}$.
Monoclinic.
Sp. gr. 3–3.2.

Cummingtonite:
$(MgFe)SiO_3$.
Monoclinic.
Sp. gr. 3.1–3.32.

Grünerite:
$FeSiO_3$.
Monoclinic.
Sp. gr. 3.713.

Hornblende:
Chiefly $Ca(MgFe)_3Si_4O_{12}$ with $(MgFe)_2(AlFe)_4Si_2O_{12}$, and $Na_2Al_2Si_4O_{12}$.
Monoclinic.
Sp. gr. 3.05–3.47.

Glaucophane:
$NaAlSi_2O_6.(FeMg)SiO_3$.
Monoclinic.
Sp. gr. 3.103–3.113.

Riebeckite:
$Na_2Fe_2Si_4O_{12}.FeSiO_3$.
Monoclinic.
Sp. gr. 3.3.

Arfvedsonite:
$(Na_2CaFe)_4Si_4O_{12}.(CaMg)_2(AlFe)_4Si_2O_{12}$.
Monoclinic.
Sp. gr. 3.44–3.45.

Occurrence.—The monoclinic amphibole group of minerals is one of the most important of the rock-making minerals. Like the pyroxenes, one form or another of amphibole may occur in almost any kind of rock, running from the most basic to the most acid, including both plutonic and volcanic rocks, the unmodified sedimentary rocks, and metamorphosed, igneous, and sedimentary rocks. The amphiboles develop extensively as secondary minerals, and especially is this true for the variety of amphibole known as uralite, which, as seen on pp. 274–275, 276–278, is derived from corresponding pyroxenes.

Tremolite and actinolite are very abundant in the schists metamorphosed from carbonate rocks, especially those rich in magnesium and iron.

They also occur in the metamorphosed calcareous fragmental sediments. Where iron is not abundant, as in the marbles, tremolite is the mineral which ordinarily develops. Where ferrous iron is plentiful actinolite normally forms. Where iron is the chief or only carbonate, grünerite ordinarily develops. Tremolite and actinolite also occur as alteration products in igneous rocks, being noted in diabases, gabbros, and more basic rocks. The secondary products frequently take the form of asbestos and jade. They are frequently associated with talc and serpentine in steatite-schists or serpentine-schists. Often, also, tremolite and actinolite are associated with pyroxene, epidote, and chlorite. These amphiboles also occur in veins. Summarizing, as metamorphic minerals, tremolite is derived from diopside, dolomite, and olivine; actinolite from ankerite, bronzite, hypersthene, olivine, parankerite, and sahlite.

Cummingtonite, the monoclinic amphibole corresponding in composition with the orthorhombic amphibole anthophyllite, occurs in various schists of metamorphic origin. It is not known as an original constituent of the igneous rocks.

Grünerite occurs most extensively in connection with magnetite and quartz, or with quartz alone, thus constituting grünerite-magnetite-quartz-schists, or grünerite-quartz-schists. The grünerite in such cases often develops as a secondary product from the alteration of siderite, as explained on page 245. Greenalite, probably having the formula $FeSiO_3.nH_2O$, occurs extensively, as in the Biwabik formation of the Mesabi series of Minnesota.[a] If such material were so deeply buried as to be altered under the conditions of the zone of anamorphism, dehydration would take place and grünerite would be formed. The mineral also occurs in the garnetiferous micaceous schists; but in some of these rocks the grünerite itself develops from the siderite, as in the case of the pure grünerite-quartz-schists and grünerite-magnetite-quartz-schists.

Hornblende is the most abundant of the amphiboles, and has a very widespread occurrence, being found as a principal constituent in various igneous rocks, including plutonic and volcanic rocks, and among the latter both in lavas and in tuffs. It also is a constituent of some of the sedimentary rocks. It is a chief constituent of many of the metamorphosed

[a] Leith, C. K., The Mesabi iron-bearing district of Minnesota: Mon. U. S. Geol. Survey, vol. 43, 1903, pp. 101–115.

rocks, especially those of igneous origin. Not infrequently it is also an abundant constituent in the metamorphosed sedimentary rocks. The schists in which the hornblende is the chief constituent, whether of aqueous or igneous origin, are generally known as amphibolites. In many other schists and gneisses which are chloritic and micaceous it is an important constituent. As a metamorphic mineral hornblende has been noted as derived from almandite, augite, melanite, and pyrope.

Glaucophane occurs abundantly in certain of the amphibole-schists, especially those which are derived from the débris of basic rocks which were originally rich in sodium. Naturally, such rocks have a somewhat limited occurrence; but where they do occur abundantly, as in the Coast Ranges of California, glaucophane is also very abundant—in fact, is the chief constituent of some of the schists, so that they may properly be called glaucophane-schists.

Riebeckite occurs in some eruptive rocks which are rich in sodium and iron, and also in metamorphosed rocks of both sedimentary and igneous origin. Like glaucophane, it may locally occur abundantly, but is not a widespread mineral.

Arfvedsonite, a soda-amphibole, very naturally occurs in the soda-bearing igneous rocks, especially in elæolite-syenites and nepheline-syenites.

Alterations.—The minerals of the monoclinic amphibole group, of such a wide variety of composition and extensive occurrence, have naturally a large number of alteration products. The more common of these are talc, serpentine, bastite, chlorite, epidote, and biotite. These are frequently accompanied by more or less magnetite, hematite, and limonite. In some cases the amphiboles alter into the zeolites, pinite, and chabazite.

Taking up the individual minerals, tremolite is most frequently transformed into talc (orthorhombic or monoclinic; sp. gr. 2.75), which may be accompanied by calcite (rhombohedral; sp. gr. 2.7135). Actinolite commonly alters into talc or serpentine (monoclinic; sp. gr. 2.575), often with the simultaneous formation of calcite, quartz (rhombohedral; sp. gr. 2.6535), and iron oxide. Cummingtonite commonly alters to bastite (orthorhombic; sp. gr. 2.6). The standard text-books do not describe the alterations of grünerite, although it is believed to alter to the iron oxides. Hornblende under weathering conditions ordinarily changes to chlorite (monoclinic; sp. gr. 2.71–2.725), which is often accompanied by epidote

(monoclinic; sp. gr. 3.38), calcite, quartz, iron oxides, and siderite (rhombohedral; sp. gr. 3.855). Under deep-seated conditions biotite (monoclinic; sp. gr. 2.90) is frequently a product of the alteration of hornblende, and with the biotite epidote may simultaneously form. Rarely serpentine is also produced. While these are the usual alterations of hornblende, in some cases, under conditions of high temperature, hornblende alters into augite (monoclinic; sp. gr. 3.4), with the simultaneous separation of magnetite (isometric; sp. gr. 5.174). Such alteration of the hornblende has been noted, according to Lacroix, both in lavas and in bombs.[a] In the lava the change is attributed to the action of the magma, being analogous to resorption; but in the bombs it is attributed to heat alone. The alterations of glaucophane and riebeckite are not described in the standard text-books. Arfvedsonite under certain conditions changes into an acmite (monoclinic; sp. gr. 3.525) free from calcium.[b] With the acmite occur limonite (amorphous; sp. gr. 3.80), magnetite, and sometimes lepidomelane (monoclinic; sp. gr. 3.0–3.2). The change of hornblende to augite and the change of arfvedsonite to acmite are the reverse of the process of uralitization.

The alteration of tremolite to talc may be written as follows:

(1) $CaMg_3Si_4O_{12}+H_2O+CO_2=H_2Mg_3Si_4O_{12}+CaCO_3+k.$

The increase in volume of the talc and calcite as compared with the tremolite is 25.61 per cent. The decrease in volume of the talc alone as compared with the tremolite is 0.83 per cent.

The alteration of actinolite to talc, supposing the excess of iron to separate as hematite (rhombohedral; sp. gr. 5.225), and supposing that the Mg : Fe : : 2 : 1, is as follows:

(2) $6CaMg_2FeSi_4O_{12}+4H_2O+6CO_2+3O=4H_2Mg_3Si_4O_{12}+6CaCO_3+3Fe_2O_3+8SiO_2+k.$

Supposing all the compounds to remain as solids the increase in volume is 20.33 per cent. If magnetite be formed instead of hematite the increase in volume is somewhat less; if limonite be formed, considerably more. If it be supposed that all the compounds except the talc are dissolved the decrease in volume is 36.51 per cent.

The alteration of actinolite to the variety of serpentine known as bastite may be written as follows:

(3) $Ca(MgFe)_3Si_4O_{12}+2H_2O+CO_2=H_4(MgFe)_3Si_2O_9+CaCO_3+2SiO_2+k.$

[a] Lacroix, A., Minéralogie de la France, Paris, 1893–95, vol. 1, pp. 668–669.

[b] Brögger, W. C., Die Mineralien der Syenitpegmatitgange der Südnorwegischen, Augit- und Nephelin-Syenite: Zeitschr. für Kryst. und Min., vol. 16, 1890, pp. 406–407.

Supposing that the Mg : Fe : : 2 : 1, the equation is—

(4) $CaMg_2FeSi_4O_{12}+2H_2O+CO_2=H_4Mg_2FeSi_2O_9+CaCO_3+2SiO_2+k.$

The increase in volume, supposing all the compounds to separate as solids, is 38.67 per cent. If only the bastite remains as a solid, the decrease in volume is 18.06 per cent.

The alteration of cummingtonite into bastite is as follows:

(5) $3(MgFe)SiO_3+2H_2O=H_4(MgFe)_3Si_2O_9+SiO_2+k.$

Supposing that the Mg : Fe : : 3 : 1, the equation is—

(6) $3Mg_3FeSi_4O_{12}+8H_2O=H_{16}Mg_9Fe_3Si_8O_{36}+4SiO_2+k.$

The increase in volume of the bastite and quartz as compared with the cummingtonite is 36.76 per cent; of the bastite alone, 14.2 per cent.

In writing equations for the alteration of hornblende into chlorite and accompanying minerals the soda-bearing part of the molecule will be omitted, since the amount of soda present in ordinary hornblende is small. Supposing that there are eight actinolite molecules in the hornblende to two of the sesquioxide molecules, that the MgO : FeO : : 2 : 1, and the $Al_2O_3 : Fe_2O_3$: : 2 : 1, that the chlorite produced is on the border line between prochlorite and clinochlore, and that the Al : Fe in the epidote as 2 : 1, the reaction may be written as follows:

(7) $8CaMg_2FeSi_4O_{12}.2Mg_4Fe_2Al_8Fe_4Si_6O_{36}+21H_2O+16CO_2=$
$2(H_{20}Mg_{12}Al_6Si_7O_{45})+2HCa_2Al_2FeSi_3O_{13}+4CaCO_3+12FeCO_3+24SiO_2+3Fe_2O_3+k.$

Provided all the compounds separate as solids the increase in volume is 25.39 per cent.

It is noticeable that the equation for the alteration of the hornblende to chlorite as a chief resultant product demands that epidote, calcite, siderite, quartz, and hematite be produced; and corresponding with this, Lacroix noted all of these minerals as accompaniments of the chloritic alteration with the exception of hematite.[a] Of course all or a larger part of the iron may pass into the form of iron oxide—magnetite, hematite, or limonite—in which case some oxygen would need to be added to the equation; the amount of CO_2 required will be less; and the oxide of iron will replace the iron carbonate partly or wholly. As these modifications can easily be made in the equation, it hardly seems necessary to write out formulæ for them.

[a] Lacroix, cit., pp. 667–668.

The change of hornblende to biotite requires the addition of potassium. The potassium can be derived from some other mineral. It is perhaps most frequently derived from orthoclase, although it is undoubtedly in many cases derived from leucite. Supposing it is derived from orthoclase, and therefore is in the form of potassium silicate, K_2SiO_3, and that the actinolite molecule in the hornblende is to the sesquioxide molecule as 2 : 3, the change may be represented as follows:

(8) $2Ca(MgFe)_3Si_4O_{12}.3(MgFe)_2(AlFe)_4Si_2O_{12}+3K_2SiO_3+SiO_2+3H_2O+2CO_2=$
$6HK(MgFe)_2(AlFe)_2Si_3O_{12}+2CaCO_3+k.$

In order to ascertain the volume relations it is necessary to make assumptions with reference to the proportions of the Mg and Fe, and of the Al and Fe. Supposing the magnesia is to the iron protoxide as 2 : 1, and the alumina is to the iron sesquioxide as 2 : 1, the equation is:—

(9) $2(CaMg_2FeSi_4O_{12}).Mg_4Fe_2Al_8Fe_4Si_6O_{36}+3K_2SiO_3+SiO_2+3H_2O+2CO_2=$
$H_6K_6Mg_6Fe_4Al_8Fe_4Si_{15}O_{72}+2CaCO_3+k.$

The increase in volume of the biotite and calcite as compared with the hornblende and quartz is 41 13 per cent. It has been noted, however, that the alteration of hornblende to biotite is often accompanied by the separation of epidote; and this is natural, since there is residual calcium in the hornblende not needed by the biotite, which could pass into the epidote. Supposing this residual calcium to pass into the epidote, the reaction may be written as follows:

(10) $8Ca(MgFe)_3Si_4O_{12}.18(MgFe)_2(AlFe)_4Si_2O_{12}+15K_2SiO_3+19SiO_2+17H_2O=$
$30HK(MgFe)_2(AlFe)_2Si_3O_{12}+4HCa_2(AlFe)_3Si_3O_{13}+k.$

In order to calculate the volume relations it may be supposed that the $MgO : FeO$ as 2 : 1, and the $Al_2O_3 : Fe_2O_3$ as 2 : 1, the equation being—

(11) $8CaMg_2FeSi_4O_{12}.6Mg_4Fe_2Al_8Fe_4Si_6O_{36}+15K_2SiO_3+19SiO_2+17H_2O=$
$10H_3K_3Mg_4Fe_2Al_4Fe_2Si_9O_{36}+H_4Ca_8Al_6Fe_4Si_{12}O_{52}+k.$

The increase in volume of the biotite and epidote as contrasted with the hornblende and quartz is 30.05 per cent. The increase in volume for equations (9) and (11) would be much less if the K_2SiO_3 were taken into account.

Where serpentine also occurs as an alteration product accompanying the chlorite, biotite, epidote, and other products, this mineral is doubtless derived from the actinolite part of the molecule, and an equation may be readily written which represents the simultaneous formation of the bastitic

form of serpentine by supposing that the number of actinolite molecules is greater than given in the above equations and that such excess of these molecules passes into bastite, according to equation (3).

While the more common alterations of hornblende are to chlorite, biotite, epidote, and accompanying minerals, as above explained, the change of hornblende into augite, just the reverse of that of augite into hornblende described on pages 274–278, does take place, and probably on a great scale at sufficient depth. The equation for one case may therefore be written:

(12) $Ca_2Mg_3Fe_3Si_8O_{24}.(MgFe)_2(AlFe)_4Si_2O_{12}+2CaCO_3=$
$2[Ca_2MgFeSi_4O_{12}.(MgFe)(AlFe)_2SiO_6]+FeCO_3+MgCO_3+k.$

If the Mg : Fe : : 2 : 1, and the Al : Fe : : 2 : 1, the equation is—

(13) $Ca_2Mg_3Fe_3Si_8O_{24}.Mg_4Fe_2Al_8Fe_4Si_6O_{36}+2CaCO_3=$
$2[Ca_2MgFeSi_4O_{12}.Mg_2FeAl_4Fe_2Si_3O_{18}]+FeCO_3+MgCO_3+k.$

The decrease in volume of the augite as compared with the amphibole is 4.13 per cent.

It is not supposed that the above equations for the alteration of hornblende necessarily represent the actual facts of specific cases. Doubtless in most instances materials from minerals aside from those given enter into the alterations, and the actual changes are more complex than represented. However, the equations very clearly show why it is that the production of chlorite from hornblende demands also the production of other minerals which Lacroix says so generally accompany chlorite. Also, they show why epidote so frequently accompanies biotite secondary to hornblende. The equations may be considered as average cases, which approximate to the alterations that actually occur in many instances. The volume relations calculated from the equations also are probably averages, for the proportions of the elements taken in the equations given are chosen from a consideration of analyses of the various minerals. The equations at least make a quantitative estimate of the relations of the original and secondary minerals, and therefore will lead to closer observations as to the minerals which result from the alteration of hornblende, and their relative proportions.

The change of arfvedsonite into acmite is so uncertain in its character that no attempt is made to write out the equations. In order to satisfactorily write equations for this alteration it is necessary to know the composition of the particular arfvedsonite which changes into the particular acmite, and what other minerals aside from the acmite are produced in the change.

The alteration of tremolite to talc, equation (1), is that of hydration and carbonation. The alteration of actinolite to talc, equation (2), is that of hydration, carbonation, desilication, and oxidation. The alteration of actinolite to bastite, equations (3) and (4), is that of hydration, carbonation, and desilication. The alteration of cummingtonite to bastite, equations (5) and (6), is that of hydration and desilication. All these changes take place with the liberation of heat and with expansion of volume, provided the compounds which form mainly separate as solids. Whether or not there is an actual increase in the volume as a result of the changes depends, of course, upon the amounts of the secondary material which is dissolved. It is therefore clear that all of these changes are those which are typical of the zone of katamorphism, and especially the belt of weathering. Moreover, some of the changes, like that of actinolite to talc and the accompanying compounds, illustrate all the processes normal to this position; i. e., hydration, carbonation, oxidation, and desilication. The fact that calcite is so frequently found associated with the talcs and serpentines secondary to tremolite, cummingtonite, and actinolite, is rendered perfectly clear by the equations; for there is always a residuum of calcium which evidently, under the conditions of the upper physical-chemical zone, unites with the carbon dioxide and produces calcium carbonate, which frequently separates as the mineral calcite in large part, but which doubtless is frequently largely or altogether carried away in solution.

The alteration of hornblende into chlorite and accompanying minerals is one of liberation of heat and expansion of volume. It is an alteration also of carbonation, and of oxidation in case some of the ferrous iron be changed to sesquioxide. It is therefore to be expected in the upper physical-chemical zone, and as a matter of fact it occurs there. The change from hornblende to biotite is a much deeper seated alteration. It involves hydration, silication, and possibly carbonation, and thus includes an unusual combination of reactions. Corresponding with these facts the change of hornblende to biotite is one which takes place under rather deep-seated conditions, particularly in connection with profound mechanical action. The physics of the interchanges between hornblende and augite are elsewhere discussed (see pp. 279–280); but it may be said that the change of the first to the second involves decrease of volume, and, corresponding with this fact, is known to take place under very deep-seated conditions of metamorphism.

IOLITE (CORDIERITE).

Iolite (cordierite):
$H_2(MgFe)_4Al_8Si_{10}O_{37}$.
Orthorhombic.
Sp. gr. 2.60–2.66.

Occurrence.—Iolite occurs in a great variety of schists and gneisses. In some cases it is so abundant as to make the rock a cordierite-gneiss. It is associated with the very heavy metamorphic minerals, such as tourmaline, andalusite, sillimanite, garnet, etc. Iolite occurs, likewise, in ejected fragments of volcanoes and as a contact mineral in connection with dikes; also rarely as an original mineral in igneous rocks.

Alterations.—The most common alteration is simple hydration. Further changes may remove some of the ferrous iron or introduce alkalies, or both, forming pinite (massive; sp. gr. 2.775). Simultaneously with this an isotropic substance is said to be formed. Iolite sometimes passes into a chlorite similar to talc.

By the hydration of iolite, according to Clarke, chlorophyllite (crystallization not given; sp. gr. 2.77) is formed.[a] Supposing the Mg and Fe to be in the same proportions both in the iolite and in the chlorophyllite, the reaction is simple:

(1) $H_2(MgFe)_4Al_8Si_{10}O_{37}+3H_2O=H_8(MgFe)_4Al_8Si_{10}O_{40}+k.$

If it be supposed that the Mg : Fe : : 3 : 1 in both compounds, the equation is—

(2) $H_2Mg_3FeAl_8Si_{10}O_{37}+3H_2O=H_8Mg_3FeAl_8Si_{10}O_{40}+k.$

The decrease in volume is 0.86 per cent.

The reaction being hydration, one would expect it to involve increase of volume, but the chlorophyllite produced is enough heavier to compensate for this. One would expect the reaction to take place in the zone of katamorphism, but observations on this point are not known to me.

The character of the product which forms simultaneously with pinite being unknown, and the character of the chlorite which forms as a secondary product not being ascertained, it seems hardly worth while to attempt to write equations for these alterations, for they would be largely conjectural.

[a] Clarke, F. W., The Constitution of the silicates: Bull. U. S. Geol. Survey No. 125, 1895, p. 83.

NEPHELITE GROUP.

NEPHELITE AND CANCRINITE.

The nephelite group includes—

Nephelite:
$NaAlSiO_4$.
Hexagonal.
Sp. gr. 2.55–2.65.

Cancrinite:
$H_6Na_6Ca\,(NaCO_3)_2Al_8Si_9O_{36}$.
Hexagonal.
Sp. gr. 2.42–2.50.

NEPHELITE.

Occurrence.—Nephelite is a sodium-aluminum silicate. Commonly the sodium is in part replaced by potassium. Nephelite occurs in both ancient and modern igneous rocks, both surface and deep seated. It is abundant in the syenite-schists and syenite-gneisses of certain localities, but is not known in the metamorphosed secondary rocks. This is doubtless due to its ready alteration. Nephelite has been produced artificially at 220° C. by a reaction between kaolinite and an alkaline carbonate. As a secondary product nephelite forms from leucite, but this alteration is not an important source of the mineral. Nephelite is also probably derived from sodalite.

Alterations.—The most frequently observed alteration of nephelite is to the zeolites, and especially to hydronephelite (hexagonal; sp. gr. 2.263), natrolite (orthorhombic; sp. gr. 2.20–2.25), thomsonite (orthorhombic; sp. gr. 2.3–2.4), and analcite (isometric; sp. gr. 2.22–2.29). Simultaneously with the formation of some of the zeolites diaspore (orthorhombic; sp. gr. 3.3–3.5), or gibbsite (monoclinic; sp. gr. 2.35), or kaolinite (monoclinic; sp. gr. 2.615), or some combination of these, is frequently formed.

The reaction for hydronephelite is—

(1) $6NaAlSiO_4+7H_2O+CO_2=2(HNa_2Al_3Si_3O_{12}.3H_2O)+Na_2CO_3+k.$

The increase in volume is 23.49 per cent.

The alteration next in importance is to natrolite and gibbsite, or to natrolite and diaspore. The reaction in the former case is:

(2) $6NaAlSiO_4+7H_2O+CO_2=2Na_2Al_2H_4Si_3O_{12}+2Al(OH)_3+Na_2CO_3+k.$

Supposing the sodium carbonate to be carried off in solution, the increase in volume would be 24.46 per cent. If two molecules less of water were added, instead of two molecules of gibbsite, two molecules of diaspore would be formed, according to the reaction:

(3) $6NaAlSiO_4+5H_2O+CO_2=2Na_2Al_2H_4Si_3O_{12}+2AlO(OH)+Na_2CO_3+k.$

In this case the increase in volume would be only 15 per cent.

In the production of thomsonite, calcium must replace the sodium. It will be assumed that this calcium is derived from calcium carbonate. The reaction will then be—

(4) $6NaAlSiO_4+7H_2O+3CaCO_3=Ca_3Al_6Si_6O_{24}.7H_2O+3Na_2CO_3+k.$

Supposing the calcium carbonate to have been brought in solution and the sodium carbonate carried away in solution, the increase in volume is 24.60 per cent.

The less common alteration of nephelite to the zeolite analcite, with the simultaneous production of diaspore or gibbsite, is expressed by the following reactions:

(5) $4NaAlSiO_4+3H_2O+CO_2=Na_2Al_2Si_4O_{12}.2H_2O+2[AlO(OH)]+Na_2CO_3+k$

or

(6) $4NaAlSiO_4+5H_2O+CO_2=Na_2Al_2Si_4O_{12}.2H_2O+2Al(OH)_3+Na_2CO_3+k.$

In the first case diaspore is simultaneously formed, and in the second case gibbsite. Supposing the sodium carbonate to be carried away in solution the increase in volume is 5.49 per cent if diaspore be formed, and 19.68 per cent if gibbsite be formed.

Alterations of nephelite to muscovite (monoclinic; sp. gr. 2.88), to hydromuscovite (pinite) (massive; sp. gr. 2.775), and to kaolinite (monoclinic; sp. gr. 2.6–2.63) have also been noticed. Where this alteration takes place the nephelite is probably a potassium-bearing one. Assuming that the amount of potassium is one-third of the sodium, the reaction may be written:

(7) $2KNa_3Al_4Si_4O_{16}+4H_2O+3CO_2=2KH_2Al_3Si_3O_{12}+H_4Al_2Si_2O_9+3Na_2CO_3+k.$

The decrease in volume of the muscovite and kaolin as compared with the nephelite is 16.50, provided the sodium carbonate is carried away in solution. The decrease is 13 per cent if the products are pinite and kaolinite. The volume of the muscovite alone is 38.46 per cent less than that of the nephelite.

Another alteration of nephelite of some importance is to sodalite (isometric; sp. gr. 2.14–2.30)—

(8) $3NaAlSiO_4+NaCl=NaCl.3NaAlSiO_4+k.$

Supposing the NaCl to be added in solution, the increase in volume is 33.14 per cent. If the sodium chloride be present as solid halite (isometric; sp. gr. 2.1–2.6), the increase in volume would be 15.64 per cent.

While the change is not recorded, it is believed to be highly probable that nephelite during mass deformation under deep-seated conditions may change into feldspar, probably albite (triclinic; sp. gr. 2.62–2.65). This reaction would require the addition of silica, as follows:

(9) $NaAlSiO_4+2SiO_2=NaAlSi_3O_8+k.$

Supposing the silica to have been present as quartz (rhombohedral; sp. gr. 2.653–2.654), the decrease in volume would be 0.41 per cent.

The formation of the zeolites, and simultaneously the minerals gibbsite or diaspore, equations (1) to (6), are all alterations of hydration, carbonation, and expansion of volume, except that of thomsonite, equation (4), which does not involve carbonation. It is therefore to be expected that these are reactions which take place in the zone of katamorphism, and such is the fact. As a result of the alteration of the nephelites to the zeolites in this zone, a part of the sodium separates and probably goes into solution as sodium carbonate, and thus we have one of the sources of this compound which so frequently occurs in underground waters, especially in volcanic regions. The formation of muscovite and kaolinite from nephelite is a reaction involving hydration and carbonation and decrease of volume, and therefore is characteristic of the zone of katamorphism. The formation of sodalite from nephelite is one which might take place in either physical-chemical zone, only in the upper zone the sodium chloride would probably be added in solution, while in the lower zone it would probably be derived from solid halite.

CANCRINITE.

Occurrence.—Cancrinite is known only in the nepheline syenites.

Alterations.—By Dana it is mentioned as altering to natrolite (orthorhombic; sp. gr., 2.225). The reaction, supposing the excess of alumina passes into gibbsite (monoclinic; sp. gr., 2.35), may be as follows:

$$H_6Na_6Ca(NaCO_3)_2Al_8Si_9O_{36}+6H_2O=$$
$$3(Na_2Al_2Si_3O_{10}.2H_2O)+2Al(OH)_3+CaCO_3+Na_2CO_3+k.$$

The increase in volume of the natrolite, gibbsite, and calcite (rhombohedral; sp. gr., 2.7135) as compared with cancrinite is 8.64 per cent. The reaction is that of hydration and breaking up of a complex compound into several simpler compounds requiring greater volume, and is therefore typical of the zone of katamorphism.

SODALITE GROUP.

SODALITE, HAÜYNITE, AND NOSELITE.

The sodalite group includes—

Sodalite:
$NaCl.3NaAlSiO_4$.
Isometric.
Sp. gr., 2.14–2.30.

Haüynite:
$Na_2Ca(NaSO_4.Al)Al_2Si_3O_{12}$.
Isometric.
Sp. gr., 2.4–2.5.

Noselite:
$Na_4(NaSO_4.Al)Al_2Si_3O_{12}$.
Isometric.
Sp. gr., 2.25–2.4.

SODALITE.

Occurrence.—Sodalite is sodium aluminum silicate with some chloride. Sodalite occurs as an original constituent in the igneous rocks, both surface and deep seated. It is not known in the secondary rocks or their metamorphosed equivalents. In fact, the occurrence of sodalite is almost identical with that of nephelite, which mineral is one of its sources.

Alterations.—The alteration products of sodalite are also identical with those of nephelite, except that nephelite passes into sodalite, and the reverse reaction is not recorded, although, as noted below, it is believed to occur. The alterations of sodalite into minerals similar to those into which nephelite alters is natural, as sodalite is made up of the nephelite molecule with the addition of sodium chloride.

Sodalite alters to the same zeolites as does nephelite, viz, to hydronephelite (hexagonal; sp. gr., 2.263), natrolite (orthorhombic; sp. gr., 2.2–2.25), thomsonite (orthorhombic; sp. gr., 2.3–2.4), and analcite (isometric; sp. gr., 2.22–2.29). Simultaneously with the formation of some of the

zeolites, diaspore (orthorhombic; sp. gr., 3.3–3.5) or gibbsite (monoclinic; sp. gr., 2.3–2.4) is frequently formed.

In the production of hydronephelite the reaction is—

(1) $2(NaCl.3NaAlSiO_4)+4H_2O+CO_2=2HNa_2Al_3Si_3O_{12}.3H_2O+2NaCl+Na_2CO_3+k.$

Supposing that the sodium chloride and sodium carbonate are dissolved, the decrease in volume is 7.25 per cent.

In the alteration of sodalite to natrolite, gibbsite or diaspore is also produced. The reaction, provided gibbsite be produced, is—

(2) $2(NaCl.3NaAlSiO_4)+7H_2O+CO_2=2Na_2Al_2H_4Si_3O_{12}+2Al(OH)_3+2NaCl+Na_2CO_3+k.$

If two molecules less of water were added, in place of the gibbsite two molecules of diaspore would be produced, according to the reaction:

(3) $2(NaCl.3NaAlSiO_4)+5H_2O+CO_2=2Na_2Al_2H_4Si_3O_{12}+2AlO(OH)+2NaCl+Na_2CO_3+k.$

Supposing the sodium chloride and sodium carbonate to be dissolved, the decrease in volume in the first case would be 6.52 per cent, and in the second case 13.62 per cent.

In the production of thomsonite the reaction is—

(4) $2(NaCl.3NaAlSiO_4)+7H_2O+3CaCO_3=Ca_3Al_6Si_6O_{24}.7H_2O+2NaCl+3Na_2CO_3+k.$

Supposing the calcium carbonate to have been in solution and the sodium chloride and sodium carbonate to be taken into solution, the decrease in volume is 6.41 per cent.

The alteration of sodalite to analcite and to diaspore may be written as follows:

(5) $4(NaCl.3NaAlSiO_4)+9H_2O+3CO_2=$
$3(Na_2Al_2Si_4O_{12}.2H_2O)+6AlO(OH)+4NaCl+3(Na_2CO_3)+k.$

If six additional molecules of water were added, as in the case of the reaction written for natrolite, gibbsite instead of diaspore would be formed. The reaction is—

(6) $4(NaCl.3NaAlSiO_4)+15H_2O+3CO_2=$
$3(Na_2Al_2Si_4O_{12}.2H_2O)+6Al(OH)_3+4NaCl+3Na_2CO_3+k.$

Supposing the sodium chloride and sodium carbonate to be taken into solution, the decrease in volume is 20.77 per cent in the case of diaspore and 10.11 per cent in the case of gibbsite.

The reaction for the alteration of sodalite to muscovite (monoclinic; sp. gr., 2.76–3) and kaolinite (monoclinic; sp. gr., 2.6–2.63), supposing potassium to replace one-fourth of the sodium of the silicate, would be—

$$(7)\quad 2(4NaCl.K_3Na_9Al_{12}Si_{12}O_{48})+12H_2O+9CO_2=$$
$$6KH_2Al_3Si_3O_{12}+3H_4Al_2Si_2O_9+8NaCl+9Na_2CO_3+k.$$

Provided the sodium chloride and sodium carbonate are dissolved, the decrease in volume is 37.07 per cent.

As in the case of nephelite, it is suspected that sodalite may pass into albite or other feldspar. However, as this change is conjectural, no reaction will be written.

The various reactions above given are analogous, both from a physical-chemical point of view and from a geological point of view, with the corresponding reactions in the case of nephelite. Hence it need only be said that the changes written are those occurring in the zone of katamorphism, in which rock fracture occurs and ground solutions are active. These ground solutions by the changes become bearers of sodium chloride and sodium carbonate.

The relations between the alterations of nephelite and sodalite illustrate very well the law of mass action. In the laboratory, if nephelite be exposed to the "slow action of fused sodium chloride with the addition of vaporized NaCl" it is changed into sodalite.[a] On the contrary, however, in nature, where water is abundant and the amount of sodium chloride is small, the reverse reaction takes place, and sodium chloride is abstracted. Probably at the same time the nephelite molecule is altered as above indicated. Thus, while observation does not as yet record nephelite as an alteration product of sodalite, it is believed to be highly probable that this mineral is really formed as a stage in the process of alteration of sodalite.

HAÜYNITE AND NOSELITE.

Occurrence.—Haüynite is sodium-calcium-aluminum silicate with some sulphate. Noselite is sodium-aluminum silicate with some sulphate.

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[a] Dana, J. D., A system of mineralogy; Descriptive mineralogy, by E. S. Dana, Wiley & Sons, New York, 6th ed., 1892, p. 430. See also Rosenbusch, Mikroskopische Physiographie, Stuttgart, 1885, p. 284.

Haüynite and noselite are common in certain igneous rocks, especially those which contain nephelite and leucite. Neither of these minerals is known in the schists and gneisses derived from the sedimentary rocks.

Alterations.—The minerals alter to zeolites, especially to natrolite (orthorhombic; sp. gr. 2.20–2.25), stilbite (monoclinic; sp. gr. 2.094–2.205), and chabazite (rhombohedral; sp. gr. 2.08–2.16). Simultaneously with certain of these alterations calcite (rhombohedral; sp. gr. 2.713–2.714) also forms.

Noselite passes into natrolite according to the following reaction:

$$(1)\quad 2Na_4(NaSO_4.Al)Al_2Si_3O_{12}+CO_2+7H_2O= 2(H_4Na_2Al_2Si_3O_{12})+2Al(OH)_3+2Na_2SO_4+Na_2CO_3+k.$$

It appears that the change requires the formation of gibbsite (monoclinic; sp. gr. 2.3–2.4) or diaspore (orthorhombic; sp. gr. 3.3–3.5), although these minerals are not recorded as forming contemporaneously with the natrolite. Supposing the gibbsite to separate as a solid, and the sodium sulphate and sodium carbonate to be taken into solution, the decrease in volume is 16.44 per cent.

The parallel reaction for the passage of haüynite into natrolite and gibbsite is as follows:

$$(2)\quad 2Na_2Ca(NaSO_4.Al)Al_2Si_3O_{12}+2CO_2+8H_2O= 2(H_4Na_2Al_2Si_3O_{12})+2Al(OH)_3+2CaCO_3+2NaHSO_4+k.$$

Supposing the gibbsite and calcite to remain as solids with the natrolite, but the sodium acid sulphate to pass into solution, the increase in volume is 4.99 per cent.

As stilbite is a calcium-bearing silicate, it may be assumed that this forms from haüynite rather than noselite. The reaction is as follows:

$$(3)\quad 6Na_2Ca(NaSO_4.Al)Al_2Si_3O_{12}+36H_2O+6CO_2= Ca_3Al_6(Si_3O_8)_6.18H_2O+12Al(OH)_3+3CaCO_3+6Na_2SO_4+3Na_2CO_3+k.$$

It appears that the reaction for the formation of stilbite thus requires the formation of calcite, and also of gibbsite or diaspore. The equation is written for the former mineral, but could readily be changed to the latter. Supposing the calcium carbonate and the gibbsite, as well as the stilbite, to be solids, and the other compounds to be taken into solution, the increase in volume is 0.460 per cent.

The reaction for the formation of chabazite from haüynite is—

(4) $4Na_2Ca(NaSO_4.Al)Al_2Si_3O_{12}+24H_2O+6CO_2=$
$Ca_3Al_6(SiO_4)_3(Si_3O_8)_3.18H_2O+4Al(OH)_3+CaSO_4+Al_2(SO_4)_3+6Na_2CO_3+k.$

This reaction again requires the formation of gibbsite or diaspore. Supposing the compound to be gibbsite, and it and the chabazite to remain as solids, and the other compounds to be taken into solution, the decrease in volume is 7.46 per cent.

The alterations of haüynite and noselite to the zeolites, calcite, and gibbsite or diaspore are all reactions of hydration and carbonation and liberation of heat. If the readily soluble compounds are dissolved, as is probable, the volume is decreased in most instances. The reactions are therefore characteristic of the zone of katamorphism.

GARNET GROUP.

GROSSULARITE, PYROPE, ALMANDITE, SPESSARTITE, MELANITE, AND UVAROVITE.

The garnet group includes the following rock-making species:

Grossularite:
$Ca_3Al_2Si_3O_{12}$.
Isometric.
Sp. gr. 3.55–3.66.

Pyrope:
$Mg_3Al_2Si_3O_{12}$.
Isometric.
Sp. gr. 3.70–3.75.

Almandite:
$Fe_3Al_2Si_3O_{12}$.
Isometric.
Sp. gr. 3.9–4.2.

Spessartite:
$Mn_3Al_2Si_3O_{12}$.
Isometric.
Sp. gr. 4.00–4.30.

Melanite:
$Ca_3Fe_2Si_3O_{12}$.
Isometric.
Sp. gr. 3.80–3.90.

Uvarovite:
$Ca_3Cr_2Si_3O_{12}$.
Isometric.
Sp. gr. 3.41–3.52.

Occurrence.—Some form of garnet is a very common mineral in a great variety of the schists and gneisses, including those which are derived from sediments and from all forms of igneous rocks, plutonic and volcanic, both lavas and tuffs. Ordinarily the garnet is a subordinate constituent in these rocks, although in some cases it becomes one of the chief constituents. The mineral has its most widespread occurrence in the metamorphosed rocks which have altered under the influence of mechanical action, or with the assistance of igneous injections, or both. Not infrequently where garnet is particularly abundant combined contact and mechanical action have assisted in furnishing the conditions favorable to its formation. In many instances the garnet develops after the mechanical action has ceased, showing that it was not the movements themselves but the other favorable conditions resulting therefrom which produced the garnets. It appears, therefore, that the conditions favorable for the extensive development of the mineral are heat, moisture, and high pressure. The mineral garnet is the most important of a group of heavy metamorphic minerals which form under the conditions mentioned. Other minerals which form under similar conditions and are frequently associated with garnet are wollastonite, cordierite, vesuvianite, scapolite, chondrodite, staurolite, andalusite, sillimanite, cyanite, tourmaline, zircon, etc. These minerals are all anhydrous, or nearly so, and mostly of a high specific gravity, many of them having a high symmetry. All of them are formed by the union of silica with bases, and are therefore produced by processes of silication. In many instances this simultaneously involves decarbonation, and this change, as already explained, p. 177, absorbs heat and lessens the volume of the compounds. They are therefore minerals which form normally in the zone of anamorphism.

Garnet thus produced can not in general be said to have been derived from any single mineral. It is usually the result of the rearrangement of material of two or more adjacent minerals. Dana notes[a] that when garnet is fused, and the material recrystallizes, the resultant minerals are usually pyroxene, melilite, monticellite, scapolite, anorthite, nephelite, etc.

This doubtless gives an indication as to some of the minerals which are rearranged under the conditions above described for the development of garnet, which are very different from those of dry fusion. Also it is

[a] Dana, J. D., A system of mineralogy; Descriptive mineralogy, by E. S. Dana, Wiley & Sons, New York, 6th ed., 1892, p. 447.

certain that various hydrous minerals furnish material for the formation of garnet, and also the limestones and dolomites. As already noted, garnet has a great variation in composition, and in a given case one of the pure species mentioned, or a combination of the molecules of two or more of them, will be formed which can be derived from the elements available. For instance, from an impure limestone, calcium-aluminum garnet, grossularite, is likely to form. In the magnesian rocks, magnesium-aluminum garnet, pyrope, is likely to be produced. In the impure aluminous carbonates of calcium, magnesium, and iron, some combination of two or more of the species grossularite, pyrope, almandite, and melanite is likely to be produced.

Garnet may be an original constituent of some of the igneous rocks. If this be so, this source of garnet is comparatively insignificant, as it is very rare indeed that garnet is found in an unaltered igneous rock. In some of the little altered igneous rocks it is found in lithophysæ, but the garnets in this position are apparently the latest products of crystallization, the conditions of their formation being analogous to those producing garnets under the ordinary conditions of rock metamorphism.

Considering the garnets individually, the following statements can be made as to their occurrence:

Grossularite is especially common in the marbles, where it is frequently associated with vesuvianite, wollastonite, diopside, etc. It also occurs in the calcareous schists and gneisses, especially in the calcareous siliceous rocks, such as calcareous quartzites and calcareous novaculites. Grossularite also is associated with common garnet in other schists and gneisses. It is recorded as being derived from melilite and gehlenite.

Pyrope, the magnesium garnet, as would be expected, is especially prevalent in peridotites and their derivatives, such as serpentine and talc, since these rocks are rich in magnesium. It also occurs in some basalts.

Almandite, one of the most widespread of the pure garnets, occurs in granites, schists, gneisses, and granulites, and thus is present in both feldspathic and feldspar-free schists. Almandite is also known in certain andesites. It rarely has crystalline forms.

Spessartite occurs in large and small grains in contact rocks, in porphyritic crystals of large size in quartzites, and is abundant in certain whetstone-schists. With topaz, it is known in lithophysæ in rhyolite.

Melanite is common in basic eruptive rocks rich in alkali. It occurs especially with nephelite and leucite in phonolites, leucitophyres, nephelinites, and tephrites. In connection with contact metamorphism it occurs with wollastonite and fassaite. It is also found in many serpentines.

Uvarovite is at home in the serpentines, particularly those which contain chromite. It is also found in the marbles.

Common garnet, ordinarily a molecular mixture of two or more of the species grossularite, pyrope, almandite, and melanite, is of course more abundant than the pure species. It occurs in such rocks as amphibolites and eclogites, in the metamorphosed diabases and gabbros, in the pyroxenic rocks and their derivatives, and in the schists and gneisses both of igneous and of sedimentary origin.

Alterations.—The minerals into which garnets alter are very numerous, chlorite (monoclinic, sp. gr. 2.71–2.725), talc (orthorhombic or monoclinic, sp. gr. 2.75), and serpentine (monoclinic; sp. gr. 2.575), however, being the more common products. Only the secondary products which occur on an important scale in the rocks will be discussed, mere mineralogical occurrences and pseudomorphs being ignored.

Alterations of grossularite are not described in the standard text-books; but it is known that meionite (tetragonal; sp. gr. 2.72) and zoisite (saussurite) (massive; sp. gr. 3.–3.04) are sometimes secondary products of garnet, and it is natural to suppose that these minerals are derived either from grossularite or from the grossularite molecule of common garnet, since grossularite contains the elements in about the right proportions to produce meionite and zoisite.

Talc and serpentine are minerals which are secondary to garnet, and from their chemical composition ought to be derived from the pyrope molecule, either from the pure garnet or from the pyrope molecule in combination with other garnet molecules. Pyrope is known to alter into chlorite. As chlorite is regarded as a molecular mixture of serpentine and amesite (crystallization not determined; sp. gr. 2.71), equations are written for its alterations into amesite and into average chlorites. Pyrope further alters into enstatite (orthorhombic; sp. gr. 3.2) and spinel (isometric; sp. gr. 3.8), these minerals frequently forming kelyphite rims about the garnet.

Almandite is recorded as altering into chlorite and into hypersthene (orthorhombic; sp. gr. 3.45) and spinel, which minerals form kelyphite rims

about the garnets. It seems probable that in such cases with the almandite there is also present the pyrope molecule, and the reactions for the formation of chlorite, spinel, and hypersthene, after almandite, as written include the pyrope molecule. In the case of the Spurr mine chlorite, secondary to garnet, the species has been determined to be aphrosiderite[a] (massive; sp. gr. 2.90).

Alterations of spessartite, melanite, and uvarovite, as pure species, are not described in the standard text-books.

Common garnet most frequently alters into chlorite. Often also it changes into epidote (monoclinic; sp. gr. 3.38) or into hornblende (monoclinic; sp. gr. 3.26). The mixture of almandite and pyrope altering into aphrosiderite, and into hypersthene and spinel, may be considered as alterations of common garnet. Where epidote is produced it is probable that the molecules from which it is derived are a mixture of grossularite and melanite. Where hornblende is produced it is probable that the molecules are a mixture of pyrope, almandite, and melanite. In the alterations of the common garnets any of the iron oxides, magnetite (isometric; sp. gr. 5.174), hematite (rhombohedral; sp. gr. 5.225), or limonite (amorphous; sp. gr. 3.80), may be produced.

The change from grossularite to meionite may be written as follows:

(1) $3Ca_3Al_2Si_3O_{12}+5CO_2=Ca_4Al_6Si_6O_{25}+5CaCO_3+3SiO_2+k.$

The increase in volume of the meionite, calcite (rhombohedral; sp. gr. 2.7135), and quartz (rhombohedral; sp. gr. 2.6535) as compared with the grossularite is 54.62 per cent.

The change of grossularite to zoisite may be written as follows:

(2) $3Ca_3Al_2Si_3O_{12}+5CO_2+H_2O=2HCa_2Al_3Si_3O_{13}+5CaCO_3+3SiO_2+k.$

The increase in volume of the zoisite, calcite, and quartz as compared with the grossularite is 40.49 per cent.

The alteration of pyrope to talc may be written in two ways, depending upon whether the excess of magnesium over that required for the for-

[a] Pumpelly, Raphael, On pseudomorphs of chlorite after garnet: Am. Jour. Sci., 3d ser., vol. 10, 1875, pp. 1–4. Penfield, S. L., and Sperry, F. L., Pseudomorphs of garnet from Lake Superior and Salida, Colo.: Am. Jour. Sci., 3d ser., vol. 32, 1886, pp. 307–311.

mation of talc is regarded as passing into magnesite (rhombohedral; sp. gr. 3.06) or into spinel. The first reaction is—

$$(3)\quad 4Mg_3Al_2Si_3O_{12}+15H_2O+3CO_2=3H_2Mg_3Si_4O_{12}+3MgCO_3+8Al(OH)_3+k.$$

The increase in volume of the talc, magnesite (rhombohedral; sp. gr. 3.06), and gibbsite (monoclinic; sp. gr. 2.35) as compared with the pyrope is 75.91 per cent. The second reaction is—

$$(4)\quad 4Mg_3Al_2Si_3O_{12}+6H_2O=3H_2Mg_3Si_4O_{12}+3MgAl_2O_4+2Al(OH)_3+k.$$

The increase in volume of the talc, spinel, and gibbsite as compared with the pyrope is 36.84 per cent.

The change of pyrope into serpentine is—

$$(5)\quad Mg_3Al_2Si_3O_{12}+5H_2O=H_4Mg_3Si_2O_9+2Al(OH)_3+SiO_2+k.$$

The increase in volume of the serpentine, gibbsite, and quartz as compared with the pyrope is 81.61 per cent.

If amesite (hexagonal plates; sp. gr. 2.71) is produced from pyrope the equation is—

$$(6)\quad Mg_3Al_2Si_3O_{12}+2H_2O+CO_2=H_4Mg_2Al_2SiO_9+MgCO_3+2SiO_2+k.$$

The increase in volume of the amesite, magnesite, and quartz as compared with the pyrope is 62.26 per cent.

In the alteration of pyrope to chlorite, supposing an intermediate chlorite be taken, the reaction is—

$$(7)\quad 3Mg_3Al_2Si_3O_{12}+8H_2O=H_{16}Mg_9Al_6Si_5O_{36}+4SiO_2+k.$$

The increase in volume of the chlorite and quartz as compared with the pyrope is 56.02 per cent. Reactions could be written which represent other varieties of chlorite.

The change of pyrope to enstatite and spinel is—

$$(8)\quad Mg_3Al_2Si_3O_{12}=2Mg\,SiO_3+MgAl_2O_4+SiO_2+k.$$

The increase in volume of the enstatite, spinel, and quartz as compared with the pyrope is 13.51 per cent.

The alteration of almandite and pyrope to chlorite (aphrosiderite),

supposing the Fe:Mg :: 2:1, about the proportion shown by analysis in the case of the Lake Superior chlorite at the Spurr mine,[a] is—

(9) $4Fe_3Al_2Si_3O_{12}.2Mg_3Al_2Si_3O_{12}+15H_2O=3H_{10}Fe_4Mg_2Al_4Si_4O_{25}+6SiO_2+k.$

The increase in volume of the aphrosiderite and quartz as compared with the garnet is 50.98 per cent.

The alteration of almandite and pyrope to hypersthene and spinel, supposing the Mg: Fe :: 1 : 1 in the hypersthene, is as follows:

(10) $Fe_3Al_2Si_3O_{12}.2Mg_3Al_2Si_3O_{12}=3MgFeSi_2O_6+3MgAl_2O_4+3SiO_2+k.$

The increase in volume of the hypersthene, spinel, and quartz, as compared with the garnet, is 12.66 per cent. If a hypersthene be produced which is less rich in iron, the amount of pyrope molecule in the original garnet must be increased.

The alteration of grossularite and melanite to epidote, supposing an average epidote be produced, in which the Al: Fe:: 2: 1 is probably—

(11) $2Ca_3Al_2Si_3O_{12}.Ca_3Fe_2Si_3O_{12}+5CO_2+H_2O=2HCa_2Al_2FeSi_3O_{13}+5CaCO_3+3SiO_2+k.$

The increase in volume of the epidote, calcite (rhombohedral, sp. gr. 2.7135), and quartz, as compared with the garnet, is 40.88 per cent. Similar equations can be written in which the pyrope molecule takes the place of the grossularite molecule in large part. In this case magnesite, instead of calcite, would be produced. Other reactions could be written for the formation of epidote, in which the original molecule is a combination of grossularite, pyrope, and melanite. The simplest case is as follows:

(12) $Ca_3Al_2Si_3O_{12}.Mg_3Al_2Si_3O_{12}.Ca_3Fe_2Si_3O_{12}+H_2O+5CO_2=$
$2HCa_2Al_2FeSi_3O_{13}+2CaCO_3+3MgCO_3+3SiO_2+k.$

In this case the increase in volume of the epidote, calcite, magnesite, and quartz, as compared with the garnet, is 39.53 per cent.

The reaction for the passage of pyrope, almandite, and melanite into hornblende may be written in many ways, depending upon the composition of the particular hornblende produced. Taking the case of an average hornblende, in which there are five of the actinolite molecules to two of the

[a] Penfield, S. L., and Sperry, F. L., On pseudomorphs of garnet from Lake Superior and Salida, Colo.: Am. Jour. Sci., 3d ser., vol. 32, 1886, pp. 307–311.

aluminous molecules, in which the MgO: FeO:: 2: 1, and Al_2O_3: Fe_2O_3:: 3: 1, the reaction is as follows:

(13) $3[2Mg_3Al_2Si_3O_{12}.Fe_3Al_2Si_3O_{12}.Ca_3Fe_2Si_3O_{12}]+4CO_2=$
$5CaMg_2FeSi_4O_{12}.2[(Mg_4Fe_2)(Al_2Fe_3)Si_6O_{36}]+4CaCO_3+4SiO_2+k.$

The increase in volume of the hornblende, calcite, and quartz, as compared with the garnet, is 24.55 per cent.

The alterations of the ferriferous garnets frequently produce iron carbonate or iron oxides. No reactions are written to illustrate these changes; nor would it be easy to express these alterations by reactions without knowing what becomes of the remainder of the garnet material.

Of course, the alterations which are written above, instead of taking place separately, may occur simultaneously. Thus the garnet may be a complex one, which contains molecules of several of the simple garnets, and there would be simultaneously produced a considerable number of secondary minerals. Thus, chlorite and hornblende, chlorite and epidote, or epidote and hornblende, might be simultaneously produced. For definite cases such as these, reactions might be written by combining the reactions for the production of the individual minerals.

An examination of the equations as written shows that in almost all cases, simultaneously with the production of the minerals which are recorded as secondary to garnet, quartz also appears, and in some cases calcium carbonate also must separate, which may be deposited in the form of calcite. Less frequently siderite and iron oxide form. It is well known that with the minerals chlorite, epidote, hornblende, etc., secondary to garnet, quartz, and calcite are often found, and that with serpentine, talc, spinel, hypersthene, and enstatite, quartz is often found. However, the quartz and calcite are usually not regarded as derived from the garnet and called minerals secondary to them. But the equations clearly show that these minerals should be regarded as secondary to garnet, just as certainly as epidote, chlorite, etc. The almost universal presence of quartz with the minerals mentioned, and the frequent presence of calcite, are thus completely explained. The equations also seem to demand in the alteration to serpentine and talc that gibbsite or diaspore shall be produced. However, some of the alumina may unite with silica and water and form kaolin. The equations suggest that a search be made for gibbsite, diaspore, and kaolin

where the serpentines and talcs are secondary to garnet. Of course, in many cases the silica, calcium carbonate, and possibly the excess of aluminum hydrate, may be dissolved and transported elsewhere, and thus their absence would be no proof that the compounds were not really produced by the alteration of the garnet.

The alterations of the various kinds of garnet into different combinations of the following minerals, serpentine, talc, chlorite, epidote, and zoisite, magnesite, and gibbsite (equations 2, 3, 4, 5, 6, 7, 9, 11, 12), are all alterations of hydration, and the majority of them of carbonation and desilication. These reactions are notable in the amount of increase in volume, ranging from 36 to 80 per cent. This increase in volume is a natural consequence of the high specific gravity of the garnet. The alterations of grossularite to meionite, calcite, and quartz (equation 1), and of pyrope, almandite, and melanite to hornblende, calcite, and quartz (equation 13), are alterations of carbonation and desilication. There can be no better illustrations of reactions characteristic of the zone of katamorphism. It will be seen (pp. 683–685) that the development of garnet is a process of the zone of anamorphism where the pressure is great and the temperature probably high. Naturally the extensive destruction of garnet is a process of the upper physical-chemical zone.

The alterations of pyrope to enstatite, spinel, and quartz (equation 8), and of almandite and pyrope together to hypersthene and spinel (equation 10), are common reactions. They do not involve hydration. They do, however, involve desilication. The increase in volume for these changes is comparatively small, 12 or 13 per cent. One would expect that these reactions would take place either in the lower part of the belt of cementation or possibly in the upper part of the zone of anamorphism.

CHRYSOLITE GROUP.

FORSTERITE, OLIVINE, AND FAYALITE.

The chrysolite group includes—

Forsterite:

Mg_2SiO_4.

Orthorhombic.

Sp. gr. 3.21–3.33.

Olivine:

$(MgFe)_2SiO_4$ where Mg : Fe : : 16 : 1, 12 : 1, to 2 : 1, in the last case the mineral being known as hyalosiderite. (Sp. gr. 3.566.)

Orthorhombic.

Sp. gr. 3.2–3.6 according to Hintze, but ordinarily being, according to Dana, 3.27–3.37.

Fayalite:

Fe_2SiO_4.

Orthorhombic.

Sp. gr. 4.1.

Occurrence.—Tschermak considers olivine as an isomorphous mixture of fayalite and forsterite. The occurrence of the three minerals is the same, except that fayalite and forsterite are not nearly so widely known as the intermediate common mineral, olivine. Olivine is an abundant constituent in intermediate and basic igneous rocks, both plutonic and volcanic, in lavas and tuffs alike. In rare cases in the volcanic rocks fayalite occurs, as, for instance, in nodules in volcanic rocks and in lithophysæ of the rhyolites of the Yellowstone Park. Forsterite also very rarely occurs in connection with volcanic rocks. Olivine is also an accessory constituent in the very basic schists and gneisses, such as the amphibolites, pyroxenites, eclogites, etc. Finally, it not infrequently occurs in marbles. In rocks of this class forsterite also rarely occurs. It therefore appears that the chrysolite group of minerals occurs most abundantly as original constituents, but are also rather widely found as secondary developments in the metamorphosed rocks, including both the carbonates and the basic schists.

Alterations.—The alterations of fayalite and forsterite are exceptional; therefore the chief alterations which are considered are those which pertain to olivine.

The most common alteration of olivine is to serpentine (monoclinic; sp. gr. 2.50–2.65). This is a change from an anhydrous orthosilicate to a hydrous orthosilicate. Doubtless this explains why serpentine rather than

talc develops so generally from the olivines, because talc is a metasilicate. Ordinarily accompanying the serpentine one or more of the following minerals may be found: Tremolite (monoclinic; sp. gr. 3.0), actinolite (monoclinic; sp. gr. 3.10), talc (orthorhombic or monoclinic; sp. gr. 2.75), hydrotalcite (hexagonal; sp. gr. 2.04–2.09), magnesite (rhombohedral; sp. gr. 3.06), breunnerite (rhombohedral; sp. gr. 3–3.2), siderite (rhombohedral; sp. gr. 3.83–3.88), quartz (rhombohedral; sp. gr. 2.6535), opal (amorphous; sp. gr. 2.15), magnetite (isometric; sp. gr. 5.174), chromite (isometric; sp. gr. 4.445), hematite (rhombohedral; sp. gr. 5.225), and limonite (amorphous; sp. gr. 3.80). One of the most frequent combinations of minerals with serpentine is magnesite, quartz or opal, and magnetite. Frequently the magnetite may partially or completely replace the hematite or limonite. The formation of the serpentine is frequently accompanied by tremolite or actinolite with iron oxide. It is much less frequently accompanied by talc. In some instances the olivine has passed directly into magnesium carbonate and hematite or limonite, but the former commonly being largely removed in solution.

Other alterations of olivine are into anthophyllite (orthorhombic; sp. gr. 3.15) into actinolite, hematite, and spinel (isometric; sp. gr. 3.8), but these are by no means comparable in importance to the change to serpentine.

Beginning with the simplest alteration to serpentine, if an olivine be taken in which the magnesium is to the iron as 3 : 1, and magnetite being the only mineral which accompanies the serpentine, the reaction may be written as follows:

(1) $3Mg_3FeSi_2O_8+6H_2O+O=3H_4Mg_3Si_2O_9+Fe_3O_4+k.$

The increase in volume of the serpentine and magnetite as compared with the olivine is 29.96 per cent.

Supposing the magnesium is to the iron as 1:1 and the iron passes into magnetite, the reaction is—

(2) $3MgFeSiO_4+2H_2O+O=H_4Mg_3Si_2O_9+Fe_3O_4+SiO_2+k.$

The increase in volume of the serpentine, magnetite, and quartz as compared with the olivine is 15.19 per cent.

If it be supposed that a third of the magnesium passes into magnesite, and that silica also separates, the reaction may be written as follows:

(3) $3Mg_3FeSi_2O_8+3CO_2+4H_2O+O=2H_4Mg_3Si_2O_9+Fe_3O_4+3MgCO_3+2SiO_2+k.$

The increase in volume of the serpentine, magnetite, magnesite, and quartz as compared with the olivine is 37.13 per cent. Supposing the Mg and Fe are present in equal proportions, the equation stands—

(4) $3Mg_2Fe_2Si_2O_8+4H_2O+2\,O=2H_4Mg_3Si_2O_9+2Fe_3O_4+2SiO_2+k.$

In this case, the olivine of which nearly corresponds to that of many rocks, the increase in volume is 12.43 per cent.

It would be easy to write other equations for different proportions of magnesium and iron in the olivine, but this seems unnecessary. Also it would be easy to write reactions by which other forms of iron compounds than magnetite are produced, such as siderite, hematite, and limonite. If this be done, and the volume reaction calculated, it will be found that the increase in volume is still greater than when magnetite forms.

Olivine is described by Becke as passing into anthophyllite (where Mg : Fe : : 4 : 1, 3 : 1, etc., orthorhombic; sp. gr. 3.1–3.2). If the proportion of the magnesium to the iron be taken as 3:1 in both the olivine and the anthophyllite, the reaction may be written as follows:

(5) $Mg_3FeSi_2O_8+2SiO_2=Mg_3FeSi_4O_{12}-k.$

The decrease in volume of the anthophyllite as compared with the original olivine and quartz is 1.48 per cent.

Various authors have also described the alteration of olivine into actinolite. Supposing that the magnesium is to the iron as 3 : 1 in both the olivine and the actinolite, and supposing the calcium to be derived from carbonate and the silica from quartz, the reaction is as follows:

(6) $3Mg_3FeSi_2O_8+4CaCO_3+10SiO_2=Mg_9Fe_3Ca_4Si_{16}O_{48}+4CO_2-k.$

The decrease in volume of the actinolite as compared with the olivine, calcite, and quartz, is 13.34 per cent.

In some instances the alteration into actinolite is described as taking place in connection with feldspar as a reaction rim. In this case the calcuim may be supposed to be derived from anorthite, as calcium silicate. The aluminum may be supposed to pass into common spinel and hercynite (isometric; sp. gr. 3.93), which are well known to be alteration products of olivine. The reaction may be:

(7) $4Mg_3FeSi_2O_8+4CaAl_2Si_2O_8=Mg_9Fe_3Ca_4Si_{16}O_{48}+3MgAl_2O_4+FeAl_2O_4-k.$

The volume decrease of the actinolite and spinels as compared with the olivine and feldspar is 7.18 per cent.

The reactions in the alterations of olivine into tremolite are parallel with those for actinolite, with the exception that no iron is present, and the mineral therefore probably forms from forsterite. The reaction may be written:

(8) $3Mg_2SiO_4+2CaCO_3+5SiO_2=2Mg_3CaSi_4O_{12}+2CO_2-k.$

The decrease in volume of the tremolite as compared with the forsterite, calcite, and silica is 12.29 per cent.

The alteration of olivine to serpentine and the accompanying minerals is the common one. It takes place in the zone of katamorphism on a great scale, both in the belt of weathering and in the belt of cementation. Corresponding with the position in the upper physical-chemical zone, the reactions occur with hydration, oxidation, expansion of volume, and liberation of heat.

The developments of anthophyllite, actinolite, and tremolite from olivine and actinolite, and of spinel from olivine and feldspar, are all deep-seated reactions of the zone of anamorphism. Corresponding to this position the change to anthophyllite, equation (5), is a reaction of silication; the changes to actinolite and to tremolite, equations (6) and (8), silication and decarbonation; and the change of olivine and anorthite to actinolite and spinel, equation (7), rearrangement of the silicates into denser silicates; and all take place with diminution of volume and absorption of heat.

SCAPOLITE GROUP.

MEIONITE, WERNERITE, and MARIALITE.

The scapolite group includes:

Meionite:
$Ca_4Al_6Si_6O_{25}$.
Tetragonal.
Sp. gr. 2.70–2.74.

Wernerite:
$mNa_4Al_3Si_9O_{24}Cl.nCa_4Al_6Si_6O_{25}$.
Tetragonal.
Sp. gr. 2.66–2.73.

Marialite:
$Na_4Al_3Si_9O_{24}Cl$.
Tetragonal.
Sp. gr. 2.566.

As is well known, the scapolite group is analogous to the plagioclase group, both consisting of sodium-aluminum-silicate molecules and calcium-aluminum-silicate molecules in various proportions. Wernerite is a combination of the marialite and meionite molecules in various ratios. Generally the ratios vary between 2 : 1 to 1 : 3.

Occurrence.—Dana summarizes the occurrence of the scapolites as follows: "(1) in volcanic rocks, as in ejected masses on Mte. Somma (meionite); (2) in crystalline limestone, often as the direct result of contact metamorphism; (3) crystalline schists, augite-gneiss, etc.; (4) as an alteration product of a plagioclase feldspar, sometimes on an extensive scale, as with amphibole."[a]

Alterations.—Dana states that the scapolites are readily alterable. The more common products of alteration are kaolin (monoclinic; sp. gr. 2.6–2.63), talc (orthorhombic or monoclinic; sp. gr. 2.7–2.8), muscovite (hydromuscovite, pinite) (monoclinic; sp. gr. 2.76–3.0), and epidote (the Al and Fe varying from 6:1 to 3:2; monoclinic; sp. gr. 3.25–3.50). It is also recorded that the scapolites alter into biotite (monoclinic; sp. gr. 2.7–3.1). Accompanying various of these alteration products quartz (rhombohedral; sp. gr 2.653–2.654) separates. Also, it is probable that in connection with some of them, gibbsite (monoclinic; sp. gr 2.3–2.4) or diaspore (orthorhombic; sp. gr. 3.3–3.5) forms, and very likely also calcite (rhombohedral; sp. gr. 2.713–2.714).

In writing out equations for the alterations to the above minerals, one is handicapped by lack of knowledge as to whether the marialite or the meionite, or a combination of the two, produces a given mineral. In this state of affairs the particular molecule is chosen which is most analogous to the compound produced. It seems probable that kaolin and talc together are produced from marialite, according to the reaction:

$$(1)\quad 2Na_4Al_3Si_9O_{24}Cl+9MgCO_3+9H_2O= 3H_4Al_2Si_2O_9+3H_2Mg_3Si_4O_{12}+3Na_2CO_3+2NaCl+6CO_2+k.$$

The increase of volume of the kaolin and talc, as compared with the marialite, is 7.69 per cent.

It may be that kaolin and calcite are also produced from meionite, as follows:

$$(2)\quad Ca_4Al_6Si_6O_{25}+6H_2O+4CO_2=3H_4Al_2Si_2O_9+4CaCO_3+k.$$

[a] Dana, J. D., A system of mineralogy; Descriptive mineralogy, by E. S. Dana, Wiley & Sons, New York, 6th ed., 1892, p. 467.

Supposing all of the $CaCO_3$ to remain as calcite, the increase of volume is 35.40 per cent.

The passage of the scapolites into muscovite may be written as follows: For marialite:

(3) $2Na_4Al_3Si_9O_{24}Cl+K_2CO_3+2H_2O+2CO_2=2KH_2Al_3Si_3O_{12}+12SiO_2+2NaCl+3Na_2CO_3+k.$

In this reaction, as in the case of the passage of the acid feldspars into muscovite, a large amount of the silica separates. The decrease in volume of the muscovite and quartz as compared with the marialite is 16.74 per cent, but if the soluble sodium salts be also taken into account the volume is increased.

For meionite the reaction may be—

(4) $Ca_4Al_6Si_6O_{25}+K_2CO_3+3CO_2+2H_2O=2KH_2Al_3Si_3O_{12}+4CaCO_3+k.$

The increase in volume of the muscovite and calcite as compared with the meionite is 29.42 per cent.

As the composition of epidote is very analogous to meionite, and as it is a calcium-bearing compound, it is thought likely, where epidote is secondary to a scapolite, that it is derived from a meionite molecule. Therefore, supposing that the epidote is one in which the aluminum is to the iron as 2 : 1, and supposing that the iron is derived from ferric oxide (Fe_2O_3), the reaction may be written as follows:

(5) $Ca_4Al_6Si_6O_{25}+Fe_2O_3+4H_2O=2HCa_2Al_2FeSi_3O_{13}+2Al(OH)_3+k.$

Supposing the hematite (hexagonal-rhombohedral; sp. gr. 5.225) to have been present as a solid, and the gibbsite to remain as a solid, the decrease in volume is 1.62 per cent. It is thought likely that iron for the reaction is often derived from iron carbonate in solution, combined with simultaneous oxidation. In this case the reaction would be—

(6) $Ca_4Al_6Si_6O_{25}+2FeCO_3+4H_2O+O=2HCa_2Al_2FeSi_3O_{13}+2Al(OH)_3+2CO_2+k.$

The increase in volume of the epidote and gibbsite as compared with the meionite is 7.55 per cent.

The passage of marialite into kaolinite and talc involves hydration, expansion of volume, and liberation of heat. The change of meionite to kaolinite involves hydration, carbonation, increase in volume, and liberation of heat. The change of the scapolites to muscovite and accompanying compounds are reactions of hydration, carbonation, increase of volume,

and liberation of heat. The change of meionite to epidote is a reaction of hydration and possibly of oxidation.

Corresponding with these facts the alterations to kaolin and talc are known to take place in the zone of katamorphism, and the same is probably true of the alterations to muscovite and epidote, although the latter reactions may be more characteristic of the belt of cementation than of the belt of weathering.

MELILITE.

Melilite:

$(CaMgNa_2)_6(AlFe)_2Si_5O_{19}$. (Groth.)

Tetragonal.

Sp. gr. 2.9–3.10.

Occurrence.—Melilite has a widespread distribution in the leucite and nephelite rocks. Aside from leucite and nephelite the most characteristic associates are augite and perovskite. Some of the rocks in which melilite occurs are leucitophyre, nepheline-syenite, and basalt.

Alterations.—The alterations of this mineral are not recorded, although from its composition there can be no doubt that in the upper physical-chemical zone it decomposes into less complicated silicates.

GEHLENITE.

Gehlenite:

$Ca_3Al_2Si_2O_{10}$.

Tetragonal.

Sp. gr. 2.9–3.07.

Occurrence.—The only occurrence of gehlenite recorded in rocks is as a contact product in limestone.

Alterations.—According to Dana it alters to talc (orthorhombic or monoclinic; sp. gr. 2.75), to fassaite (monoclinic; sp. gr. 2.965–3.291), and to grossularite (isometric; sp. gr. 3.605).

The change to grossularite involves the addition of SiO_2, thus:

$$Ca_3Al_2Si_2O_{10}+SiO_2=Ca_3Al_2Si_3O_{12}+k.$$

The decrease in volume of the grossularite as compared with the gehlenite is 4.42 per cent. If the SiO_2 be added as a solid, the decrease in volume is 18.56.

As gehlenite is so rare, and the manner of the alteration into talc and fassaite is not clear, no attempt is made to write equations for the changes.

VESUVIANITE.

Vesuvianite:
$HR''_6Al_3Si_5O_{21}$ (Clarke).
Tetragonal.
Sp. gr. 3.35–3.45.

Clarke states that the R_6 in the typical mineral is replaced by calcium and magnesium in the proportion of 5:1, giving $HCa_5MgAl_3Si_5O_{21}$.

Occurrence.—Vesuvianite occurs in ancient ejections of Vesuvius. It is most abundant in marbles. It is also found in various gneisses and schists, especially those which are calcareous. It often forms in connection with contact action. It is frequently associated with such other metamorphic minerals as garnet, and also the micas and chlorites.

Alterations.—From the literature it is impracticable to ascertain which particular garnet, mica, or chlorite forms from a certain vesuvianite, and the accompanying minerals which must simultaneously form are unknown; it therefore does not seem advisable to attempt to write equations representing the alterations, since they must be so largely speculative.

ZIRCON GROUP.

The only important rock-making mineral of the zircon group is zircon.

Zircon:
$ZrSiO_4$.
Tetragonal.
Sp. gr. 4.66–4.70.

Occurrence.—Zircon is especially common in marble. It also occurs both in massive igneous rocks, such as syenite and granite, and in the schists and gneisses.

Alterations.—According to Clarke the only alteration described is that of hydration, producing hydrous zircon (malacon) (tetragonal; sp. gr. 3.905), the reaction being:

$$3ZrSiO_4 + H_2O = H_2Zr_3Si_3O_{13}.$$

The increase in volume in the change is 24.05 per cent.

ALUMINUM-SILICATE GROUP.

TOPAZ, ANDALUSITE, SILLIMANITE, AND CYANITE.

The aluminum-silicate group includes—

Topaz:
$Al_2F_2SiO_4$ or $Al_2(F,OH)_2SiO_4$.
Orthorhombic.
Sp. gr. 3.4–3.6.

Andalusite:
Al_2SiO_5.
Orthorhombic.
Sp. gr. 3.16–3.20.

Sillimanite:
Al_2SiO_5.
Orthorhombic.
Sp. gr. 3.23–3.24.

Cyanite (*disthene*):
Al_2SiO_5.
Triclinic.
Sp. gr. 3.56–3.67.

Occurrence.—Topaz is a much less common mineral than andalusite, sillimanite, and cyanite. Like them, it occurs in the schists and gneisses of sedimentary origin, especially those in which other fluorine minerals are found, such as tourmaline and beryl. Unlike andalusite, sillimanite, and cyanite, it is sometimes found in cavities in fresh volcanic rocks, as, for instance, rhyolite.

Andalusite is a frequent constituent of the metamorphosed sedimentary rocks, especially of the argillaceous kinds. It often occurs in crystals, including many other minerals in the partly metamorphosed sedimentary rocks; but is also found in large, well-formed crystals in the schists. Frequently in the metamorphosed sedimentary rocks its development has been promoted by the contact effect of igneous rocks, especially the granitic rocks. Its most characteristic associates are sillimanite and cyanite. With the former it frequently has parallel intergrowths. Also it is frequently associated with garnet and staurolite, and not infrequently with tourmaline. Andalusite is rare, if indeed not altogether absent in the metamorphosed igneous rocks.

Sillimanite is a common mineral in the strongly metamorphosed sedimetary rocks, such as schists and gneisses, where it frequently replaces

andalusite to a large extent. Like andalusite, its development may be promoted by the presence of intrusive rocks, especially granites. In such cases sillimanite frequently develops nearer the intrusive masses than does the andalusite, the sillimanite therefore being the mineral which forms under conditions of more advanced metamorphism. It is frequently associated with garnet and with spinel and staurolite, sometimes with iolite (cordierite). Sillimanite is derived from andalusite, biotite, corundum, cyanite, diaspore, and gibbsite.

The occurrence and associates of cyanite are similar to those of sillimanite; but a very frequent additional associate is corundum, and where formed by the assistance of igneous rocks the cyanite is likely, on the average, to be closer to the intrusive than the sillimanite, although of course they ordinarily overlap. As a metamorphic mineral, cyanite is derived from andalusite, corundum, diaspore, and gibbsite.

Tremolite, actinolite, and diopside are frequent associates of andalusite, sillimanite, and cyanite, especially of the last two.

The special homes of the aluminum-silicate group of minerals are the metamorphosed argillaceous sedimentary rocks. As is well known, kaolin is one of the chief constituents of such rocks, and doubtless it is from this mineral in large part, under deep-seated conditions, that the aluminum-silicate minerals are formed. If it be supposed that these heavy minerals develop from kaolin, the process would be one of dehydration and separation of silica. This silica may separate either as quartz or may unite with other compounds, such as calcium and magnesium or other bases, to form silicates. The breaking up of the kaolin may be represented by the following equation:

(1) $H_4Al_2Si_2O_9 = Al_2SiO_5 + 2H_2O + SiO_2 + k.$

Supposing the mineral produced were andalusite, the volume of the andalusite and quartz is 25.40 per cent less than that of the kaolin. If it be supposed that calcium carbonate is present at the same time, and that the freed silica unites with it, the equation may be written:

(2) $H_4Al_2Si_2O_9 + CaCO_3 = Al_2SiO_5 + CaSiO_3 + 2H_2O + CO_2 + k.$

In this case the volume of the andalusite and wollastonite is 32.32 per cent less than that of the kaolin and calcite. If the heavier mineral sillimanite or cyanite be produced the decrease in volume is even greater.

While for the sake of simplicity wollastonite is supposed to form, the more frequent association of the aluminum-silicate group is with tremolite, actinolite, and diopside. For the first and last of these minerals the freed silica unites with the calcium and magnesium together, and for the second with the calcium, magnesium, and iron. The equations representing the changes are analogous to (2), and the volume changes are in the same direction.

Alterations.—The standard stated alterations of the aluminum-silicate group are to talc (steatite) (massive; sp. gr. 2.75) and to muscovite (damourite) (monoclinic; sp. gr. 2.88). It is recorded also that topaz and andalusite alter to kaolin (monoclinic; sp. gr. 2.615). Occasionally also andalusite may alter into the heavier mineral cyanite (triclinic; sp. gr. 3.56–3.67).

The alterations of the minerals into talc require an entire change of base; that is, from aluminum silicates to magnesium silicates. The reactions being those of the zone of katamorphism, the most probable source of the magnesium is doubtless the carbonate, which may be derived from the decomposition of magnesium rocks such as the pyroxenites, olivinites, etc. The process, however, requires the separation of aluminum either as corundum (rhombohedral; sp. gr. 4.025), corundophilite (monoclinic; sp. gr. 2.90), diaspore (orthorhombic; sp. gr. 3.40), gibbsite (monoclinic; sp. gr. 2.35), or some other form. Since the reaction takes place in the upper physical-chemical zone, gibbsite will be regarded as the product formed. The change of the aluminum-silicate minerals to muscovite requires the addition of potassium. This is doubtless derived from the liberation of potassium during the decomposition of the potash feldspars, and will therefore be regarded as added as a carbonate. The change from andalusite to cyanite is simply a molecular one, the result being a mineral of great specific gravity. It has already been seen that andalusite is a product of less intense metamorphism, and that more intense metamorphism produces sillimanite and cyanite. The change of andalusite to these heavier minerals is therefore one which requires deep-seated conditions, and is characteristic of the zone of katamorphism.

The equations representing the change of andalusite, sillimanite, and cyanite to talc with gibbsite may be written as follows:

(1) $4Al_2SiO_5+3MgCO_3+13H_2O=H_2Mg_3Si_4O_{12}+8Al(OH)_3+3CO_2+k.$

The decrease in volume of the talc as compared with the andalusite is 32.37 per cent; as compared with the sillimanite, 31.20 per cent; as compared with the cyanite, 23.12 per cent. But if the gibbsite be included as a solid the increases in volume are 97.67 per cent, 101.09 per cent, and 124.71 per cent, respectively.

The change of the three minerals to kaolin may be written as follows:

$$(2)\quad 2Al_2SiO_5+5H_2O=H_4Al_2Si_2O_9+2Al(OH)_3+k.$$

The change in volume of the kaolin as compared with the andalusite is a decrease of 3.15 per cent; as compared with. the sillimanite, a decrease of 1.47 per cent; and as compared with the cyanite, an increase of 10.11 per cent. But if the gibbsite be a solid, the increases in volume are 61.87 per cent, 64.67 per cent, and 84.02 per cent, respectively.

The alterations of the same minerals to muscovite (damourite) may be written as follows:

$$(3)\quad 6Al_2SiO_5+K_2CO_3+11H_2O=2H_2KAl_3Si_3O_{12}+6Al(OH)_3+CO_2+k.$$

The decrease in volume of the muscovite as compared with the andalusite is 9.55 per cent; as compared with the sillimanite, 7.98 per cent; the increase as compared with the cyanite is 2.83 per cent. But if the gibbsite be regarded as a solid, the increases in volume are 55.47 per cent, 58.16 per cent, and 76.74 per cent, respectively.

The alterations of the aluminum-silicate minerals to talc, kaolin, or muscovite, with the accompanying gibbsite, are all reactions of hydration. They involve great increase of volume, from 55 to 125 per cent. To produce the original heavy aluminum-silicate minerals in the zone of anamorphism undoubtedly required great condensation of volume. When the reactions are reversed in the zone of katamorphism, there is a correspondingly great expansion of volume. The change of the heavy aluminum-silicate minerals to the much lighter hydrous minerals gives one of the best illustrative cases of typical reactions of the zone of katamorphism.

The change of andalusite to cyanite, as already explained, being a molecular one, involves a volume relation inversely as the specific gravity, and therefore by the change the volume is decreased 12.03 per cent. The change of andalusite to cyanite is a reaction of the zone of anamorphism.

EPIDOTE GROUP.

ZOISITE, EPIDOTE, PIEDMONTITE, AND ALLANITE.

The epidote group includes the following minerals:

Zoisite:
$Ca_2(AlOH)Al_2(SiO_4)_3$.
Orthorhombic.
Sp. gr. 3.25–3.37.

Epidote:
$Ca_2(AlOH)(AlFe)_2(SiO_4)_3$ where Al:Fe as 6:1 to 3:2.
Monoclinic.
Sp. gr. 3.25–3.50.

Piedmontite:
$Ca_2(AlOH)(MnAl)_2(SiO_4)_3$.
Monoclinic.
Sp. gr. 3.404.

Allanite (orthite):
$Ca_2(AlOH)(AlCeFe)_2(SiO_4)_3$.
Monoclinic.
Sp. gr. 3.5–4.2.

Occurrence.—Zoisite is not known as an original pyrogenic constituent of igneous rocks. It is found in the schists and gneisses, especially those containing the amphiboles. Thus it is very common in the amphibolites, glaucophane-schists, eclogites, etc. Zoisite frequently occurs with albite as one of the constituents of the so-called saussurites, which develop as an alteration of the basic feldspars, especially in gabbros. Zoisite also occurs in the altered granites and other acid igneous rocks, although it is, on the whole, less abundant than in the more basic rocks, but in some localities it is plentiful even in the acid rocks. Zoisite is a very frequent constituent in grits, graywackes, and other sediments of similar composition. In such rocks the minerals were partly altered to zoisite during the formation of the sedimentary rocks, and this zoisite is to be classed with the allogenic constituents of the mechanical sediments. Zoisite further develops in the altered sedimentary rocks as a frequent and sometimes abundant product of metamorphism. From the foregoing statement of occurrence it is plain that zoisite develops in the zone of katamorphism, and especially in the belt of cementation. As shown under the discussion of the other minerals, it is seen that zoisite may be derived from the following minerals: Corundum, diaspore, gibbsite, grossularite, and the plagioclases.

Epidote, like zoisite, is rarely if ever a pyrogenic constituent in igneous rocks. It is, however, a secondary constituent in all varieties of metamorphosed igneous rocks, whether plutonic or volcanic, whether lavas or tuffs. It is an allogenic constituent of the sedimentary rocks, and it extensively develops in the sedimentary rocks as a secondary product. It is particularly likely to form in rocks rich in calcium and iron, whether igneous or sedimentary; and thus is especially abundant in those metamorphosed igneous rocks which contain ferriferous varieties of pyroxene and amphibole, and in metamorphic sedimentary rocks which contain a considerable amount of calcium, as, for instance, calcareous schists and gneisses and marble. In the metamorphosed rocks epidote occurs alike in those which have a strongly developed schistose or gneissose structure and in those which have merely undergone metasomatic change. It is found as one of the important filling constituents of amygdaloids. It frequently develops at the contact of two rocks, especially an igneous rock with other rocks, either igneous or sedimentary. A list of different rock species which contain epidote includes almost every variety of massive, schistose, semischistose, and little altered igneous and sedimentary rocks. Epidote is, in fact, one of the most important secondary constituents of all the silicates. It is an almost constant accompaniment of the chlorites. Wherever the calcium-iron-magnesium-silicate rocks break up, the magnesium passing into chlorite, a part of the calcium and iron is likely to pass into epidote. The equations for these alterations may be found under the minerals from which epidote is derived. Where epidote becomes so abundant as to be a chief constituent it may give a name to a rock; for instance, epidosite. From the foregoing statements it is apparent that epidote develops abundantly under mass-static and under mass-mechanical conditions. It forms with ease and on a great scale in the belt of cementation of the zone of katamorphism, and it is probable that it develops to some extent in the zone of anamorphism. Whether it forms at all in the belt of weathering can not be stated. Epidote is derived from the following minerals: Anorthoclase, augite, biotite, garnet, hornblende, melanite, microcline, orthoclase, the plagioclases, and the scapolites.

Piedmontite, or manganese-epidote, is apt to replace epidote in those schists and gneisses in which manganese happens to be an important constituent. Thus it is rather common in certain manganese-bearing schists of

Japan, in the manganese-chlorite-sericite-gneisses of eastern United States, and at other localities. In some cases piedmontite occurs as nuclei surrounded by ordinary epidote. Piedmontite is occasionally so abundant as to be one of the chief constituents of rocks.

Allanite occurs as an original subordinate constituent of a great number of eruptive rocks, such as granite, rhyolite, diorite, tonalite, andesite, dacite, and syenite. In short, it is a common accessory in the acid and intermediate eruptives, but is not so characteristic of the basic eruptive rocks. It also occurs in the metamorphic rocks, such as the schists and gneisses, especially those which are calcareous, and it may occur also in the marbles.

Alterations.—Definite alterations of zoisite, epidote, and piedmontite are not recorded. But it is certain in the belt of weathering that zoisite and epidote break up into calcite (rhombohedral; sp. gr. 2.7135), quartz (rhombohedral; sp. gr. 2.6535), iron oxides, kaolin (monoclinic; sp. gr. 2.615), and perhaps gibbsite (monoclinic; sp. gr. 2.35); and piedmontite and allanite alter into other minerals in a similar fashion.

It has already been seen that in the alteration of mica, pyroxene, amphibole, and other minerals chlorite and zoisite are frequent simultaneous products which together use up all the material of the original minerals. It has also been noted that the chlorite and epidote are abundantly developed together in the sedimentary rocks. If the conditions so change that these sedimentary rocks or other rocks in which epidote and zoisite have formed in the zone of katamorphism become so deeply buried as to pass into the zone of anamorphism, it is highly probable that the constituents which form epidote and zoisite and those which form chlorite reunite to produce minerals that are on the average denser, such as mica, amphibole, pyroxene, etc., out of which they are originally developed. This is believed to be probable from the fact that in the most profoundly metamorphosed sedimentary rocks, those which are true schists and gneisses, little or no epidote and chlorite is contained, unless they have again been subjected to the conditions of the upper physical-chemical zone. Such schists and gneisses, having been derived from and traced into ordinary sediments, in all probability did originally contain both chlorite and epidote, which have doubtless united to reproduce heavy minerals similar to those from which epidote and chlorite formed originally.

It is not easy to approach accuracy in writing equations for the alterations of the epidotes in the belt of weathering. In the equations given below it is supposed that the calcium passes into carbonate, that the Al (OH) goes into gibbsite, that the remainder of the aluminum goes into kaolin, and that the excess of silica separates as quartz. In the epidote the Al is supposed to be to the Fe as 2:1, and the iron is supposed to pass into limonite (amorphous; sp. gr. 3.8). Upon these suppositions the alterations stand—

For zoisite—

(1) $Ca_2(AlOH)Al_2(SiO_4)_3+2CO_2+3H_2O=2CaCO_3+Al(OH)_3+H_4Al_2Si_2O_9+SiO_2+k$

and for epidote—

(2) $Ca_6(AlOH)_3Al_4Fe_2Si_9O_{36}+6CO_2+8\frac{1}{2}H_2O=$
$6CaCO_3+3Al(OH)_3+2H_4Al_2Si_2O_9+Fe_2O_3.1\frac{1}{2}H_2O+5SiO_2+k.$

The increase in volume of all the compounds formed as compared with the zoisite is 66.22 per cent, and as compared with the epidote is 69.08 per cent.

Of course there are many other ways in which the equations could be written. All of the aluminum might pass into gibbsite or diaspore and more quartz form. The iron may pass into hematite in whole or in part, etc. While all this is true, it is believed that the above equations represent correctly the fundamental fact that by hydration and carbonation zoisite and epidote in the belt of weathering pass into simpler compounds.

Similar reactions could be written for the alterations of piedmontite and allanite, but considering the comparative rarity of these compounds this will not be done.

AXINITE.

Axinite:

$HCa_3Al_2BSi_4O_{16}$. (In some cases part of the Ca is replaced by Fe and Mn.)

Triclinic.

Sp. gr. 3.271–3.294.

Occurrence.—Axinite occurs as a secondary constituent in basic eruptive rocks, such as the diabases and gabbros. It is found to some extent in the schists and gneisses, and particularly in those bearing abundant pyroxene and amphibole. It also occurs in altered sedimentary rocks as a product

formed in connection with the contact action of such rocks as granites, granulites, diabases, and gabbros. In such positions the formation of axinite is usually regarded as assisted by fumarole action.

Alterations.—Apparently the alterations which axinite undergoes in rocks have not been worked out, as they are not recorded in the standard text-books.

PREHNITE.

Prehnite:

$H_2Ca_2Al_2Si_3O_{12}$.

Orthorhombic.

Sp. gr. 2.8–2.95.

Occurrence.—Prehnite is almost identical in its occurrence with the zeolites (see pp. 331–333). It is therefore especially prevalent in the basic and intermediate rocks, such as anorthosite, basalt, diabase, gabbro, andesite, diorite, and syenite; also it occurs to some extent in granites and gneisses, where it may be associated with epidote. In the igneous rocks it is especially prevalent in the volcanics, since these are usually more porous. Like the zeolites, it is a very frequent occupant of amygdaloidal cavities, and also of cracks and crevices in the rocks. As already intimated, the most constant associates of prehnite are the zeolites. Prehnite occurs to some extent in the schists and gneisses, including those derived from igneous rocks, such as the amphibolites, and from aqueous rocks, such as the marbles. In some cases it is found in cavities in sedimentary rocks which have been metamorphosed by granitic or granulitic intrusions. As a secondary mineral prehnite is often derived from analcite, laumontite, mesolite, natrolite, the plagioclases, and scolecite. Fused prehnite yields wollastonite and ankerite.

Alterations.—The only alteration which I have been able to note in reference to prehnite is to chlorite (monoclinic; sp. gr. 2.71–2.725). This change requires the substitution of magnesium for calcium. Supposing the chlorite were amesite (hexagonal plates; sp. gr. 2.71), the change might be expressed:

$$H_2Ca_2Al_2Si_3O_{12}+2MgCO_3+H_2O=H_4Mg_2Al_2SiO_9+2SiO_2+2CaCO_3+k.$$

Ignoring the carbonates, the increase of volume of the chlorite and quartz (rhombohedral; sp. gr. 2.6535) as compared with the prehnite is 3.27 per cent. The change is one of hydration and desilication, and would be expected to take place in the zone of katamorphism.

HUMITE GROUP.

CHONDRODITE, HUMITE, AND CLINOHUMITE.

The humite group includes:

Chondrodite:
$[Mg(F.OH)]_2Mg_3Si_2O_8$.
Monoclinic.
Sp. gr. 3.1–3.2.

Humite:
$[Mg(F.OH)]_2Mg_5Si_3O_{12}$.
Orthorhombic.
Sp. gr. 3.1–3.2.

Clinohumite:
$[Mg(F.OH)]_2Mg_7Si_4O_{16}$.
Monoclinic.
Sp. gr. 3.1–3.2.

In all the above the hydroxide (OH) replaces a part of the fluorine.

Occurrence.—The humites occur in masses of magnesian limestones and rocks bearing carbonates ejected by volcanoes. Chondrodite has a somewhat widespread occurrence in the marbles of eastern United States. In such cases it is sometimes, at least, a contact mineral. Frequently it is accompanied by spinel.

Alterations.—The most frequent alterations of the humites are to serpentine (monoclinic; sp. gr. 2.50–2.65) and brucite (rhombohedral; sp. gr. 2.38–2.4). In the equations for the alterations the hydroxide will be ignored. The reactions may be written as follows:

(1) $(MgF)_2Mg_3Si_2O_8+3H_2O=H_4Mg_3Si_2O_9+Mg(OH)_2+MgF_2+k.$
(2) $2[(MgF)_2Mg_5Si_3O_{12}]+9H_2O=3H_4Mg_3Si_2O_9+3Mg(OH)_2+2MgF_2+k.$
(3) $(MgF)_2Mg_7Si_4O_{18}+6H_2O=2H_4Mg_3Si_2O_9+2Mg(OH)_2+MgF_2+k.$

The increase in volume of the serpentine and brucite as compared with chondrodite, from which it is derived, is 30.15 per cent; as compared with humite, 35.53 per cent; as compared with clinohumite, 38.39 per cent.

The alterations of humite to serpentine and brucite involve hydration, expansion of volume, and liberation of heat. They are therefore typical reactions of the zone of katamorphism.

TOURMALINE.

Tourmaline is a complicated aluminum silicate, which may be of any one of four different types or intermolecular growths of these types. According to Clarke, the formulæ for these types are—[a]

Tourmaline:

$NaHR_3Al_8B_3Si_6O_{31}$ (R in some cases being lithium and hydrogen).
$NaH_3Mg_2Al_7B_3Si_6O_{31}$ (Mg frequently being replaced by Fe).
$NaH_4Mg_3Al_6B_3Si_6O_{31}$.
$NaH_5Mg_4Al_5B_3Si_6O_{31}$.
Rhombohedral.
Sp. gr. 2.98–3.20.

Occurrence.—Tourmaline rather frequently occurs in the marbles and in the calcareous schists. It also has a rather widespread occurrence, although generally not as an abundant mineral, in granites, gneisses, schists, and granulite. In these rocks it frequently occurs in such relations to dikes of igneous rocks, especially of pegmatites, as to suggest that its development is promoted by contact action. Because of the boron, tourmaline has generally been regarded as evidence of fumarole action. Certain it is that boron is not usually a constituent of the ordinary sediments, and to account for this element, especially where the tourmaline is abundant, as it occasionally is in the schists, would seem to require its introduction from an outside source, either by gaseous or by aqueous solutions.

Alterations.—Mineral specimens of tourmaline are recorded as altering into mica, chlorite (monoclinic; sp. gr. 2.71–2.725), and steatite (massive; sp. gr. 2.794). However, in rocks tourmaline is one of the more permanent minerals, and the chemical additions and subtractions which occur in the alterations are so little known, and the exact nature of the tourmaline from which individual minerals are derived is so uncertain, that it is not thought advisable to attempt to write all the reactions representing these changes. If one assumes a definite tourmaline and a definite mica as being produced from it, it is easy to write a reaction. For instance, supposing that normal biotite (monoclinic; sp. gr. 2.90) is derived from a tourmaline of the composition of the last of the four formulæ given, that the additional alkalies are added in the forms of carbonates, that the free boric acid

[a] Clarke, F. W., The constitution of the silicates: Bull. U. S. Geol. Survey No. 125, 1895, pp. 56–57. An alternative form has been proposed by Penfield.

passes into borax, and that the excess of alumina separates as gibbsite (monoclinic; sp. gr. 2.35), the reaction is—

$$4NaH_3Mg_4Al_3B_3Si_6O_{31}+4K_2CO_3+Na_2CO_3=$$
$$8HKMg_2Al_2Si_3O_{12}+3Na_2B_4O_7+4Al(OH)_3+5CO_2+k.$$

The decrease in volume of the biotite as compared with the tourmaline is 6.75 per cent; but if the gibbsite be included the increase of volume is 3.96 per cent.

STAUROLITE.

Staurolite:
$HFeAl_5Si_2O_{13}$
Orthorhombic.
Sp. gr. 3.65–3.77.

Occurrence.—Staurolite is similar in its occurrence to garnet, but apparently requires more intense metamorphic action for it to begin to form. Its most widespread occurrence is in the schists and gneisses of sedimentary origin. It also develops in profoundly metamorphosed rocks of eruptive origin, but it is not known as an original constituent in any eruptive rock. Like garnet, it may be abundantly developed in the zone of anamorphism in rocks which are cut by intrusives. The conditions favorable to its formation are therefore similar to those which produce garnet (see pp. 300–302) and such minerals as tourmaline, andalusite, sillimanite, and cyanite, with which it is associated. It is evidently a mineral which derives its materials from various other minerals, the elements being recombined into the more compact form of staurolite under deep-seated conditions.

Alterations.—The only alterations recorded for staurolite are to talc (orthorhombic or monoclinic; sp. gr. 2.75), to chlorite (monoclinic; sp. gr. 2.71-2.725), and to muscovite (damourite) (monoclinic; sp. gr. 2.76–3.0). The first two minerals are essentially magnesian ones, although if the chlorite be aphrosiderite (massive; sp. gr. 2.90) a considerable amount of iron may be present. It is therefore clear that in the change to talc and chlorite magnesium must be derived from some other compounds. As the alterations are those which occur in the zone of katamorphism, it may be supposed that the magnesium is in the form of carbonate, since magnesium carbonate is an almost universal constituent of ground waters in the upper physical-chemical zone. The alteration to muscovite requires an entire loss of the iron and the addition of potassium. It is therefore clear that some

potassium mineral must also be concerned in this alteration. Staurolite rocks usually contain orthoclase, or at least some potash feldspar. It may be supposed that these potash feldspars break up into kaolin at the same time, thus furnishing the potassium necessary for the change.

The change of staurolite to talc may be written as follows:

(1) $2HFeAl_5Si_2O_{13}+3MgCO_3+15H_2O+O=H_2Mg_3Si_4O_{12}+Fe_2O_3+10Al(OH)_3+3CO_2+k.$

The decrease of the volume of the talc as compared with the staurolite is 44.02 per cent; but if the gibbsite (monoclinic; sp. gr. 2.35) be included the increase in volume of the two is 90.96 per cent.

In the change to chlorite the most aluminous one is chosen, amesite (hexagonal plates; sp. gr. 2.71), since staurolite is so heavily aluminous Moreover, it is supposed that the iron in the chlorite is to the magnesium as 1:3. On these suppositions the reaction may be written:

(2) $2HFeAl_5Si_2O_{13}+10H_2O+6MgCO_3=2H_8Mg_3FeAl_4Si_2O_{18}+2Al(OH)_3+6CO_2+k.$

The increase of volume of the chlorite and gibbsite as compared with the staurolite is 103.58 per cent

The change of staurolite to muscovite may be written:

(3) $3HFeAl_5Si_2O_{13}+K_2CO_3+14H_2O+O=2H_2KAl_3Si_3O_{12}+Fe_3O_4+9Al(OH)_3+CO_2+k.$

The decrease in volume of the muscovite as compared with the staurolite is 24.96 per cent; but if the magnetite (isometric; sp. gr. 5.174) and gibbsite be included the increase in volume would be 68.08 per cent, and if hematite (rhombohedral; sp gr. 5.225) or limonite (amorphous; sp. gr. 3.8) form, instead of magnetite, the increase would be still greater.

In the above equations it is entirely possible that the magnesium may be added in some other form than that given, and the resultant compounds be different. The same thing may be said of the potassium. It is uncertain what becomes of the excess of aluminum. In the equations the aluminum is regarded as passing into the gibbsite. However, the presence of abundant gibbsite is not recorded among the alterations of staurolite, although frequently corundum (rhombohedral; sp. gr. 4.025) occurs in connection with it; but it is by no means certain that this corundum is one of the results of the alteration of the staurolite; indeed, it is more probable that the corundum formed from gibbsite at the same time the staurolite developed.

In short, the above reactions are probably as unsatisfactory as any that have been written, because the text-books do not record what minerals accompany the talc, chlorite, and muscovite as a result of the transformation of the staurolite. It is certain that in each case some other minerals must be produced.

ZEOLITE GROUP.

The zeolites are a great group of hydrous silicates about which there seems to be no consensus of opinion as to the species in the group, as to the composition of the species, or as to their classification. Since Groth and Clarke are among the latest authors to discuss this group, their formulæ are used, Groth's being placed first and Clarke's second when he differs from Groth. Groth's formulæ are put into an empirical form, and the subordinate constituents which may replace the chief bases are omitted. The differences between the formulæ given and Dana's also are pointed out. The important rock-making zeolites are as follows, ranged from basic to acid:

THOMSONITE, HYDRONEPHELITE, NATROLITE, MESOLITE, SCOLECITE, ANALCITE, APOPHYLLITE, EPISTILBITE, HEULANDITE, STILBITE, PHILLIPSITE, HARMOTOME, GISMONDITE, CHABAZITE, GMELINITE, AND LAUMONTITE.

Thomsonite:

$(CaNa_2)\ Al_2Si_2O_8.2\frac{1}{2}H_2O$ (Dana agrees with Groth.)

$Ca_3Al_6Si_6O_{24}.7H_2O$

Orthorhombic.

Sp. gr. 2.3–2.4.

Hydronephelite:

$HNa_2Al_3Si_3O_{12}.3H_2O$

$HNa_2Al_3Si_2O_{12}.3H_2O$

Hexagonal.

Sp. gr. 2.263.

Natrolite:

$Na_2Al_2Si_3O_{10}.2H_2O$ (Dana agrees with Groth.)

Orthorhombic.

Sp. gr. 2.20–2.25.

Mesolite:

$H_2Na_2CaAl_4Si_6O_{21}.4H_2O$. (Dana makes all water that of hydration.)

$H_8Na_2CaAl_4Si_6O_{24}.H_2O$.

Monoclinic and triclinic.

Sp. gr. 2.29.

Scolecite:

$H_2CaAl_2Si_3O_{11}.2H_2O$. (Dana agrees with Groth.)
Monoclinic.
Sp. gr. 2.16–2.4.

Analcite:

$Na_2Al_2Si_4O_{12}.2H_2O$. (Dana agrees with Groth.)
Isometric.
Sp. gr. 2.22–2.29.

Apophyllite:

$H_7KCa_4Si_8O_{24}.4\frac{1}{2}H_2O$. (Dana agrees with Groth.)
$H_{14}Ca_4Si_6O_{23}$.
Tetragonal.
Sp. gr. 2.3–2.4.

Epistilbite:

$H_6Ca_2Al_4Si_{11}O_{33}.7H_2O$. (Dana varies from both, but is nearer Groth. His formula is $H_4CaAl_2Si_6O_{18}.3H_2O$.)
$Ca_3Al_6Si_8O_{48}.16H_2O$.
Monoclinic.
Sp. gr. 2.25.

Heulandite:

$H_4CaAl_2Si_6O_{18}.3H_2O$. (Dana agrees with Groth.)
$Ca_3Al_6Si_{18}O_{48}.16H_2O$.
Monoclinic.
Sp. gr. 2.18–2.22.

Stilbite (desmine):

$Ca_4Al_8Si_{18}O_{48}.18H_2O$. (Dana's formula is nearly the same as Clarke's: $H_4(Na_2Ca)Al_2Si_6O_{18}.4H_2O$.)
$Ca_3Al_6Si_{18}O_{48}.18H_2O$.
Monoclinic.
Sp. gr. 2.094–2.205.

Phillipsite:

$(K_2Na_2Ca)_3Al_6Si_{10}O_{32}.12H_2O$. (Dana's formula is nearly like Clarke's: $(K_2Ca)Al_2Si_4O_{12}.4\frac{1}{2}H_2O$.)
$K_2Ca_2Al_6Si_{12}O_{36}.14H_2O$.
Monoclinic.
Sp. gr. 2.2.

Harmotome:

$Ba_3Al_6Si_{10}O_{32}.12H_2O$. (Dana varies from each. His formula is $(K_2Ba)Al_2Si_3O_{14}.5H_2O$.)
$Ba_3Al_6Si_{14}O_{40}.14H_2O$.
Monoclinic.
Sp. gr. 2.44–2.50.

Gismondite:

$Ca_3Al_6Si_4O_{24}.12H_2O$. (Dana's formula is one of the molecules given.)
$Ca_3Al_6Si_4O_{24}.12H_2O$.
Monoclinic.
Sp. gr. 2.265.

Chabazite:

$Ca_3Al_6Si_{10}O_{32}.16H_2O$. (Dana agrees with Clarke as to the amount of Si. His formula is $(CaNa_2)Al_2Si_4O_{12}.6H_2O$.)
$Ca_3Al_6Si_{12}O_{36}.18H_2O$.
Rhombohedral.
Sp. gr. 2.08–2.16.

Gmelinite:

$Na_6Al_6Si_{10}O_{32}.16H_2O$. (Dana varies from each. His formula is $(Na_2Ca)Al_2Si_4O_{12}.6H_2O$.)
$Na_3Al_3Si_7O_{20}.9H_2O$.
Rhombohedral.
Sp. gr. 2.04–2.17.

Laumontite:

$H_4CaAl_2Si_4O_{14}.2H_2O$. (Dana agrees with Groth.)
$Ca_3Al_6Si_{12}O_{36}.12H_2O$.
Monoclinic.
Sp. gr. 2.25–2.36.

Occurrence.—The zeolites are not known as original pyrogenic constituents of igneous rocks. As secondary minerals they are most abundantly found in basic lavas and allied rocks, including both glassy and crystallized kinds. The zeolites occur in these rocks, both in the ordinary feldspathic varieties, such as basalt and trachyte, and in those containing leucite, nephelite, sodalite, etc., and especially in those which are somewhat vesicular. The zeolites also develop abundantly in the deep-seated equivalents of the basalts in such rocks as the diabases, gabbros, etc. The zeolites are less prevalent, although far from rare, in the diorite and syenite families, including both the ordinary syenites and nepheline-syenites. Finally, the zeolites are far from uncommon in the more acid rocks, such as those of the granite family. In short, the zeolites may occur in almost any variety of the igneous rocks, but, as already said, are most prevalent in the basic group. In the sedimentary rocks the zeolites may be allogenic constituents separate from other minerals, or an alteration product of partly decomposed minerals. Also, after the deposition of material in the fragmental rocks the zeolites may develop as alteration products. Hence the zeolites are constituents of the altered sedimentary rocks, of the semimetamorphosed

sedimentary rocks, and of the schists and gneisses of sedimentary origin, which, after becoming schists and gneisses, have been subjected to agencies of alteration in the zone of katamorphism.

The zeolites develop from many minerals, but especially from the plagioclase feldspars and from the leucites, sodalites, nephelites, etc. From the plagioclases many of the zeolites are produced. The following may be regarded as derived from anorthite: Thomsonite, gismondite, laumontite, phillipsite, heulandite, epistilbite, stilbite, chabazite, and scolecite. The following may be regarded as derived from albite: Analcite and natrolite. Mesolite may be regarded as derived from albite and anorthite together. Since the intermediate plagioclases contain both the anorthite and the albite molecules, all of the above minerals may be derived from oligoclase, andesine, labradorite, and bytownite, as may also mesolite. So far as recorded the derivations of the zeolite minerals from the nephelites, leucites, and sodalites are as follows: Thomsonite from nephelite and sodalite; hydronephelite from nephelite and sodalite; natrolite from nephelite, sodalite, haüynite, and noselite; analcite from leucite, nephelite, and sodalite; stilbite from haüynite and noselite; chabazite from haüynite and noselite. The zeolites are also derived from other minerals as follows: Analcite from laumontite, natrolite from apatite and chabazite, etc.

It is hardly worth while to consider the occurrence of each of the zeolites. It may be said, however, that the calcium-bearing zeolites are most apt to form in the calcareous rocks, and the soda zeolites in the rocks rich in soda. Thus stilbite, scolecite, and similar minerals are likely to form in the calcareous rocks and limestones, while hydronephelite, natrolite, and analcite, and similar minerals, are especially likely to form from the rocks containing soda feldspars and nephelites, leucites, and sodalites. The sodium-calcium zeolites, such as thomsonite, mesolite, and phillipsite, may occur in the calcareous rocks, such as the limestones, in the igneous soda rocks, such as the nephelite rocks, and in the basalts and similar rocks.

In the rocks in which they occur the zeolites may be found (1) within the mass of the rock as alteration products of the minerals; (2) in amygdules, filling the vacuoles of the igneous rocks; and (3) in other openings of all kinds, such as fractures, the pores of sediments, etc.

The development of the zeolites in nearly all cases requires hydration and expansion of volume, as shown under the discussions of the particular minerals from which they form. Their formation, therefore, tends to fill up the crevices and cracks in rocks, even if no material be furnished from an extraneous source. It may be that the zeolitization combined with other alterations furnishes sufficient material to entirely fill the vacuoles of many amygdaloids without material being furnished from an extraneous source. (See pp. 631–634.) However, it is doubtless the case that much of the material of the zeolites which is deposited in the belt of cementation is derived by solution from the belt of weathering. As shown under the individual minerals from which the zeolites develop, the conditions for the formation of these minerals are those of the zone of katamorphism, both in the belt of weathering and in that of cementation.

In the belt of cementation, in which hydration is perhaps the most characteristic reaction and alterations can take place with expansion of volume, the zeolites form on a great scale. Conforming with these statements are the observations made by Daubrée[a] that zeolites can be formed experimentally in the presence of abundant water at temperatures of about 50° C. Pointing in the same direction is the fact stated by Renard[b] that phillipsite has extensively formed at the bottom of the sea at temperatures not far from 0° C.

While the zeolites develop chiefly in the belt of cementation, it is certain that in very humid regions they form in the belt of weathering. But it is also certain that to a great extent the zeolites are also destroyed in the belt of weathering. This is especially the case in hot arid regions.

Alterations.—The most comprehensive statement as to the alterations of the zeolites is that given by Clarke.[c] His statements are as follows: (1) Natrolite alters into prehnite (orthorhombic; sp. gr. 2.875); (2) mesolite alters into prehnite; (3) scolecite alters into prehnite; (4) analcite alters into albite (triclinic; sp. gr. 2.635), and (5) orthoclase (monoclinic; sp. gr. 2.57) and prehnite; (6) apophyllite alters into pectolite (monoclinic; sp. gr. 2.73); (7) heulandite alters into albite, and (8) into orthoclase;

[a] Daubrée, A., Études synthétiques de géologie expérimentale, Paris, 1879, pt. 1, pp. 199, 205–207.

[b] Murray, John, and Renard, A. F., Report of the scientific results of the voyage of H. M. S. *Challenger*, 1873–1876; Deep-sea deposits, London, 1891, pp. 400–411.

[c] Clarke, F. W., The constitution of the silicates: Bull. U. S. Geol. Survey No. 125, 1895, pp. 32–45.

(9) stilbite alters into albite, and (10) into orthoclase; (11) chabazite alters into natrolite (hexagonal-rhombohedral (Hintze), orthorhombic (Dana); sp. gr. 2.225); (12) laumontite alters into albite, (13) into orthoclase and prehnite, and (14) into analcite (isometric; sp. gr. 2.255).

These alterations may be expressed by the following equations, the numbers of the equations corresponding to the numbers of the alterations. In writing these equations, whether Groth's or Clarke's formula is used depends on which is more nearly analogous to the formula of the mineral produced.

(1) $Na_2Al_2Si_3O_{10}.2H_2O+2CaCO_3=H_2Ca_2Al_2Si_3O_{12}+Na_2CO_3+CO_2+H_2O-k.$

(2) $H_2Na_2CaAl_4Si_6O_{21}.4H_2O+3CaCO_3=2H_2Ca_2Al_2Si_3O_{12}+Na_2CO_3+2CO_2+3H_2O-k.$

(3) $H_2CaAl_2Si_3O_{11}.2H_2O+CaCO_3=H_2Ca_2Al_2Si_3O_{12}+2H_2O+CO_2-k.$

(4) $Na_2Al_2Si_4O_{12}.2H_2O+2SiO_2=2NaAlSi_3O_8+2H_2O-k.$

(5) $3(Na_2Al_2Si_4O_{12}.2H_2O)+4CaCO_3+K_2CO_3=$
$2KAlSi_3O_8+2H_2Ca_2Al_2Si_3O_{12}+3Na_2CO_3+2CO_2+4H_2O-k.$

(6) $H_{14}Ca_4Si_6O_{23}+Na_2CO_3=2HNaCa_2Si_3O_9+6H_2O+CO_2-k.$

(7) $H_4CaAl_2Si_6O_{18}.3H_2O+Na_2CO_3=2NaAlSi_3O_8+CaCO_3+5H_2O-k.$

(8) $H_4CaAl_2Si_6O_{18}.3H_2O+K_2CO_3=2KAlSi_3O_8+CaCO_3+5H_2O-k.$

(9) $Ca_3Al_8Si_{18}O_{48}.18H_2O+3Na_2CO_3=6NaAlSi_3O_8+3CaCO_3+18H_2O-k.$

(10) $Ca_3Al_6Si_{18}O_{48}.18H_2O+3K_2CO_3=6KAlSi_3O_8+3CaCO_3+18H_2O-k.$

(11) $Ca_3Al_6Si_{12}O_{36}.18H_2O+2Al(OH)_3+4Na_2CO_3=$
$4H_4Na_2Al_2Si_3O_{12}+3CaCO_3+CO_2+13H_2O-k.$

(12) $Ca_3Al_6Si_{12}O_{36}.12H_2O+2Na_2CO_3+CO_2=4NaAlSi_3O_8+Al_2O_3+3CaCO_3+12H_2O-k.$

(13) $Ca_3Al_6Si_{12}O_{36}.12H_2O+CaCO_3+K_2CO_3=$
$2KAlSi_3O_8+2H_2Ca_2Al_2Si_3O_{12}+2CO_2+10H_2O-k.$

(14) $Ca_3Al_6Si_{12}O_{36}.12H_2O+3Na_2CO_3=3(Na_2Al_2Si_4O_{12}.2H_2O)+3CaCO_3+6H_2O-k.$

The decreases in volumes are as follows: Prehnite as compared with the natrolite, equation (1), 16.12 per cent; prehnite as compared with mesolite, equation (2), 15.05 per cent; prehnite as compared with scolecite, equation (3), 16.66 per cent; albite as compared with the analcite and quartz, equation (4), 17.25 per cent; orthoclase and prehnite as compared with analcite, equation (5), 14.09 per cent; pectolite as compared with apophyllite, equation (6), 19.48 per cent; albite as compared with heulandite, equation (7), 25.03 per cent; orthoclase as compared with heulandite, equation (8), 18.44 per cent; albite as compared with stilbite, equation (9), 31.67 per cent; orthoclase as compared with stilbite, equation (10), 25.66 per cent; natrolite as compared with chabazite, equation (11), 4.58 per

cent; albite as compared with laumontite, equation (12), 34.92 per cent; orthoclase and prehnite as compared with laumontite, equation (13), 17.75 per cent; and analcite as compared with laumontite, equation (14), 4.30 per cent.

In calculating the volume relations the carbonates, and in equation (11) the aluminum hydrate, are ignored. If these compounds were taken into account the decreases in volume would in some cases be somewhat more, in others somewhat less. To ignore these side compounds seems the best course, since the added and subtracted salts may be in other forms than those given.

For the most part the alterations, so far as the bases are concerned, are remarkably simple, involving only the interchange between the alkalies, sodium and potassium, or between sodium and the alkaline earth calcium, or the addition of the bases sodium or calcium. They are all reactions of dehydration, partial or complete. Many of them are reactions of decarbonation and one, equation (4), is a reaction of silication. Presumably they all take place with the absorption of heat. While nothing can be ascertained as to the actual conditions under which the changes take place, one would expect them to occur in the zone of anamorphism, for a number of the reactions reverse those of the zone of katamorphism. In the latter zone the alteration of the feldspars into the zeolites is well known. The reverse changes, those of analcite, heulandite, stilbite, and laumontite into albite and orthoclase, for which equations are written, would be hardly likely to take place in the same zone. At any rate the alterations of the feldspars into the zeolites and the zeolites into the feldspars present a very interesting case of reversible reactions discussed subsequently. (See pp. 366–369.)

It is further certain that the zeolites as extensively formed in the belt of cementation, in the belt of weathering break up, by carbonation and hydration, into the simpler compounds, such as the carbonates of the alkalies and the alkaline earths, diaspore or gibbsite, kaolin, and quartz. Hypothetical reactions could readily be written for these changes similar to those worked out for zoisite and epidote (pp. 322–323); but since so little is known as to the definite minerals which are formed from each zeolite, this is hardly worth while at the present stage of knowledge.

MICA GROUP.

MUSCOVITE, PARAGONITE, BIOTITE, AND PHLOGOPITE.

The mica group includes the following rock-making species:

Muscovite:
$(H,K)AlSiO_4$. (Normal muscovite $KH_2Al_3Si_3O_{12}$.)
Monoclinic.
Sp. gr. 2.76–3.0.

Paragonite:
$H_2NaAl_3Si_3O_{12}$.
Monoclinic.
Sp. gr. 2.78–2.90.

Biotite:
$(H,K)_2(MgFe)_2Al_2Si_3O_{12}$. (Dana.) (Proportion of Mg:Fe varies widely. Normal biotite: $KHMg_2Al_2Si_3O_{12}$. (Clarke.))
Monoclinic.
Sp. gr. 2.7–3.1.

Phlogopite:
$KH_2Mg_3AlSi_3O_{12}$.
Monoclinic.
Sp. gr. 2.78–2.85.

MUSCOVITE.

Muscovite, as already noted, is hydrogen-potassium-aluminum silicate.

Occurrence.—Muscovite is an abundant constituent in the plutonic rocks, but is rather rare as a constituent in the volcanic rocks. It is one of the most abundant constituents of the metamorphosed rocks, being a chief mineral in many metamorphosed sedimentary and many metamorphosed igneous rocks. As a secondary constituent, it is derived from many other minerals. The more important of these are feldspar, including both orthoclase and plagioclase, nephelite, sodalite, leucite, the scapolites, spodumene, topaz, andalusite, and cyanite. It is also recorded as a pseudomorph after tourmaline, garnet, beryl, and cordierite. There is little doubt also that muscovite in the metamorphosed rocks is largely formed from the materials of the zeolites. Some of the minerals, such as nephelite, sodalite, and leucite, from which the muscovite is derived, occur only in the igneous rocks. Others of them, such as the zeolites, occur only in rocks of altered or secondary nature. Others of the minerals from which muscovite is derived, such as topaz, cyanite, and andalusite, are chiefly metamorphic constituents.

Still others from which muscovite is derived, such as the feldspars, may be original constituents of the igneous rocks, or they may be original or secondary constituents of the sedimentary rocks. It is therefore clear that muscovite has an unusual variety of sources, and consequently it may be expected in almost any variety of rock except the volcanics. It is, however, a more characteristic constituent of the acidic and intermediate rocks than of the basic rocks.

In summary, muscovite is derived from anorthoclase, diaspore, gibbsite, leucite, microcline, nephelite, orthoclase, plagioclase and orthoclase, scapolites, sodalite, and spodumene. The muscovite damourite is derived from andalusite, corundum, cyanite, sillimanite, staurolite, and topaz.

Alterations.—The minerals to which muscovite alters are not nearly so abundant as those from which it is derived. One of the most frequent alterations is that of hydration, a part of the potassium being replaced by hydrogen; or at the same time it may take up other bases and thus the mineral may pass into vermiculite, a somewhat indefinite compound to which no formula can be assigned. Muscovite also alters into serpentine (monoclinic; sp. gr. 2.50–2.65) and into the steatitic form of talc (massive; sp. gr. 2.7–2.8). Probably simultaneously with the formation of these minerals gibbsite (monoclinic; sp. gr. 2.3–2.4) or diaspore (orthorhombic; sp. gr. 3.3–3.5) forms, although the contemporaneous formation of these minerals is not mentioned. Muscovite also may alter into the soda-mica paragonite (monoclinic; sp. gr. 2.78–2.90).

The reactions by which muscovite passes into serpentine and talc are very uncertain. If the magnesium were supposed to be derived from a carbonate and all of the silica of the muscovite went into the resultant compounds, the reactions may be written as follows:

For serpentine:

$$(1)\quad 2KH_2Al_3Si_3O_{12}+9MgCO_3+13H_2O=3H_4Mg_3Si_2O_9+6Al(OH)_3+K_2CO_3+8CO_2+k.$$

For talc:

$$(2)\quad 4KH_2Al_3Si_3O_{12}+9MgCO_3+17H_2O=3H_2Mg_3Si_4O_{12}+12Al(OH)_3+2K_2CO_3+7CO_2+k.$$

The increase in volume of the serpentine as compared with the muscovite is 16.56 per cent, and the decrease of the talc 25.23 per cent. But if the magnesium carbonate be contributed by solutions, and the gibbsite remains as a solid with the serpentine and talc, the increase in volume of the ser-

pentine and gibbsite as compared with the muscovite is 88.44 per cent, and of the talc and gibbsite 46.69 per cent.

The change of muscovite to paragonite merely requires the substitution of sodium for potassium, and may be written as follows:

(3) $2H_2KAl_3Si_3O_{12}+Na_2CO_3=2H_2NaAl_3Si_3O_{12}+K_2CO_3+k.$

The decrease in volume is 2.67 per cent.

Muscovite under deep-seated conditions is a mineral which is practically permanent. In fact, under these conditions, as already indicated, it is produced by the alteration of other minerals. The above alterations of muscovite, resulting in the formation of vermiculite, serpentine, and talc, with gibbsite all occur in the zone of katamorphism, and especially in the belt of weathering. Even under the conditions of the surface belt the processes of change are exceedingly slow. Corresponding with this position, the changes take place with increase of volume and liberation of heat.

PARAGONITE.

Paragonite is hydrous sodium-aluminum silicate.

Occurrence.—Paragonite is not certainly known as an original pyrogenic constituent in igneous rocks. It is found especially in the metamorphosed igneous rocks and in the semimetamorphosed and completely metamorphosed sedimentary rocks. In many so-called sericite rocks it is probable that a portion of the micaceous mineral is paragonite rather than muscovite. Paragonite is especially likely to occur in the metamorphic rocks, instead of muscovite, where the original rocks, either igneous or sedimentary, bear a considerable amount of sodium. Very frequently associated with paragonite are the heavy metamorphic minerals, such as cyanite, staurolite, garnet, tourmaline, etc. In certain places muscovite has been noted as passing to paragonite, and thus the potassium mica is a source for the soda mica.

In summary, paragonite as a metamorphic mineral is derived from anorthoclase, muscovite, and plagioclases.

Alterations.—Alterations of paragonite are not recorded in the standard text-books. However, there can be little doubt that this mineral undergoes a set of alterations in the zone of katamorphism, and one would expect that these alterations would be analogous to those which take place with muscovite.

BIOTITE.

Biotite is hydrogen-potassium-magnesium-aluminum silicate, a part of the magnesium frequently being replaced by iron.

Occurrence.—Biotite is an original chief constituent of many of the igneous rocks, both plutonic and volcanic, and ranging from those which are acid to those which are basic. It is a very abundant secondary constituent in the slates, schists, and gneisses, developing on a great scale in the metamorphosed rocks, both igneous and sedimentary. As a secondary constituent it seems usually not to be derived from a single mineral, as is frequently the case with muscovite, but is produced from material furnished by two or more minerals. For instance, it is frequently a reaction product between magnetite and other minerals, the magnetite furnishing the iron for the biotite, the other constituents being derived from such minerals as the pyroxenes, amphiboles, and feldspars. A frequent case is the formation of biotite from the pyroxenes, feldspars, and magnetite. The feldspars and feldspathoids frequently furnish the potassia, parts of the alumina, and silica. The pyroxenes and amphiboles frequently furnish a part of the magnesia, alumina, and silica. Dolomite is often a source of the magnesia. The oxides and carbonate of iron are the most frequent sources of this element.

In summary, as a metamorphic mineral, biotite is derived from anorthoclase, augite, hornblende, microcline, orthoclase, and the scapolites.

Alterations.—Perhaps the most frequent alterations of biotite are to hydrobiotite (probably monoclinic; sp. gr. 2.90, average of biotite) and to chlorite (monoclinic; sp. gr. 2.80). It also alters into epidote (monoclinic; sp. gr. 3.25–3.50); rarely it alters into hypersthene (orthorhombic; sp. gr. 3.40–3.50) and sillimanite (orthorhombic; sp. gr. 3.23–3.24); and in some cases it apparently alters into serpentine (monoclinic; sp. gr. 2.575). Its alteration into the above minerals may be accompanied by the separation of quartz (rhombohedral; sp. gr. 2.6535), and if the biotite be ferriferous, by the formation of magnetite (isometric; sp. gr. 5.174), or other iron oxide.

The alteration of biotite into serpentine probably requires the simultaneous production of kaolin (monoclinic; sp. gr. 2.615) and gibbsite (monoclinic; sp. gr. 2.35). Supposing that all the magnesium of normal biotite

goes into the serpentine, and that all the silica not required for the production of this mineral passes into the kaolin, the reaction is as follows:

(1) $6KHMg_2Al_2Si_3O_{12}+18H_2O+3CO_2=$
$4H_4Mg_3Si_2O_9+5H_4Al_2Si_2O_9+2Al(OH)_3+3K_2CO_3+k.$

Supposing all the serpentine, kaolin, and gibbsite to remain as solids, and the potassium carbonate to go into solution, the increase in volume is 14.26 per cent.

The change of biotite into hydrobiotite may be written:

(2) $2HKMg_2Al_2Si_3O_{12}+7H_2O+CO_2=2(H_2Mg_2Al_2Si_3O_{12}.3H_2O)+K_2CO_3+k.$

The increase in volume is 3.8 per cent.

The alteration into chlorite, supposing all the alumina and silica to remain in the altered mineral, and the additional magnesia to be added in the form of a carbonate, may be written as follows:

(3) $2KHMg_2Al_2Si_3O_{12}+4MgCO_3+5H_2O=2[H_2Mg_4Al_2Si_3O_{12}.4(OH)]+K_2CO_3+3CO_2+k.$

The increase in volume, supposing the magnesium carbonate is added in solution and the potassium carbonate goes into solution, is 22.92 per cent.

The reaction by which biotite passes into epidote is uncertain. If the ferrous iron of the biotite be changed to sesquioxide during the alteration, and if the proportion of magnesium to iron be supposed to be 3:1 in the biotite, and of aluminum to iron 4:1 in the epidote, the reaction may be written:

(4) $6H_2K_2Mg_3FeAl_4Si_6O_{24}+20CaCO_3+4CO_2+3O=$
$2(H_5Ca_{10}Al_{12}Fe_3Si_{15}O_{65})+6SiO_2+18MgCO_3+6K_2CO_3+H_2O+k.$

The ratios assumed of the magnesium and iron for the biotite, and of aluminum and iron for the epidote, are near means. If it be assumed that the iron of the biotite is not changed to sesquioxide, but that the sesquioxide of iron for the epidote must be derived from another source, the reaction takes a very different form. Under such an assumption the epidote may be produced from normal biotite, and the equation stand as follows:

(5) $30KHMg_2Al_2Si_3O_{12}+6Fe_2O_3+40CaCO_3+35CO_2+H_2O=$
$4(H_5Ca_{10}Al_{12}Fe_3Si_{15}O_{65})+30SiO_2+12AlO(OH)+60MgCO_3+15K_2CO_3+k.$

By adding thirteen molecules of water instead of one, twelve molecules of gibbsite instead of twelve molecules of diaspore (orthorhombic; sp. gr. 3.40) will be produced.

In equation (4), supposing the calcium carbonate to be added in solution and the magnesium carbonate and the potassium carbonate to be removed in solution and the silica to remain as a solid, the decrease in volume is 14.86 per cent.

In equation (5), supposing the biotite and iron oxide to be solids, the calcium carbonate to be added in solution, the magnesium and potassium carbonates to remain in solution, but the epidote, silica, and diaspore to remain as solids, the decrease in volume is 18.45 per cent. If gibbsite instead of diaspore be produced the decrease in volume will not be so much.

If it be supposed that the aluminum passes into spinel (isometric; sp. gr. 3.8) instead of diaspore or gibbsite, and spinel is known to form in connection with biotite, the number of molecules of magnesium carbonate would be reduced by six in equation (4); that is, to 54. $6MgAl_2O_4$ would replace the $12AlO(OH)$. No water would need to be added, and five molecules of water would be produced. Finally, only twenty-nine molecules of CO_2 would need to be added. Therefore the equation would be:

$$(6)\quad 30KHMg_2Al_2Si_3O_{12}+6Fe_2O_3+40CaCO_3+29CO_2= 4H_5Ca_{10}Al_{12}Fe_3Si_{15}O_{65}+30SiO_2+6MgAl_2O_4+54MgCO_3+15K_2CO_3+5H_2O+k.$$

In this case the volume of the resultant epidote, spinel, and silica, would be 14.71 per cent less than that of the biotite and 18.15 per cent less than that of the biotite and hematite.

It is a well-known fact that chlorite secondary to biotite is usually accompanied by epidote and quartz. Comparing the equation (3) for the formation of chlorite with equation (4) for epidote, we see why these two minerals with quartz are frequently formed at the same time. For the formation of chlorite from biotite additional magnesium is needed. For the formation of epidote additional calcium is necessary and magnesium is left over. If instead of magnesium and calcium carbonates being added, as suggested in equations (3) and (4), only calcium carbonate were available, the excess of magnesium produced by the passage into epidote may go into the chlorite, and thus epidote and chlorite be simultaneously produced.

Combining these equations, (3) and (4), and supposing the iron oxide to be furnished by hematite, the reaction may be written as follows:

(7) $60KHMg_2Al_2Si_3O_{12}+6Fe_2O_3+40CaCO_3+76H_2O=$
$30[H_2Mg_4Al_2Si_3O_{12}.4(OH)]+4(H_5Ca_{10}Al_{12}Fe_3Si_{15}O_{65})+30SiO_2+12AlO(OH)+$
$30K_2CO_3+10CO_2+k.$

The increase in volume of the epidote, chlorite, quartz, and diaspore together, as compared with the biotite and hematite, would be 1.81 per cent.

If biotite alters to hypersthene and sillimanite it may be presumed, in order to furnish the necessary iron for the hypersthene, that the biotite is an iron-bearing one. If the magnesium be to the iron as 3 : 1, and the hypersthene be one in which the same ratio prevails, the reaction may be written as follows:

(8) $H_2K_2Mg_3FeAl_4Si_6O_{24}+CO_2=Mg_3FeSi_4O_{12}+2Al_2SiO_5+H_2O+K_2CO_3+k.$

The decrease in volume of the hypersthene and sillimanite, as compared with the biotite, is 24.68 per cent.

In the majority of the above reactions a formula for biotite is used which contains no iron. The majority of biotites in nature do contain some iron. If this material be present, simultaneously with the formation of other minerals magnetite (isometric; sp. gr. 5.174), hematite (rhombohedral; sp. gr. 5.225), and the other oxides of iron may be produced. The abstraction of the iron oxides is accompanied commonly by a change in color of the altering biotite from brown to green. The presence of these compounds, however, in subordinate quantities will not alter the main conclusions as to the volume relations above given.

The alterations of biotite, serpentine, kaolin, and gibbsite, into hydrobiotite and chlorite, equations (1) to (3), are all reactions which are known to occur in the zone of katamorphism, corresponding with which position they are all reactions of hydration, and the first two also of carbonation. Where chlorite and epidote form together, the reaction is that of hydration, and doubtless this change also takes place in the zone of katamorphism. The formation of hypersthene and sillimanite from biotite usually occurs in connection with contact reactions of igneous rocks; it is, therefore, a reaction requiring high temperature. Also the minerals

sillimanite and hypersthene do not form at the surface, but at depth. Corresponding with these physical-chemical facts, the reaction is one of dehydration and reduction of volume.

PHLOGOPITE.

Phlogopite is potassium-hydrogen-magnesium-aluminum silicate.

Occurrence.—Phlogopite has an occurrence which is somewhat different from that of biotite. It is especially characteristic of metamorphosed impure carbonates, such as dolomitic marbles. In these rocks it is often associated with pyroxene, amphibole, etc.

Alterations.—The most frequent alterations of phlogopite are to hydrophlogopite (monoclinic; sp. gr. 2.303, kerrite) and chlorite (monoclinic; variety of penninite; sp. gr. 2.649). It is also said to alter to talc (orthorhombic or monoclinic; sp. gr. 2.7–2.8). In these last two alterations gibbsite (monoclinic; sp. gr. 2.3–2.4) or diaspore (orthorhombic; sp. gr. 3.40) must simultaneously separate.

The reactions for these changes are as follows:

For hydrophlogopite:

$$(1)\ 2H_2KMg_3AlSi_3O_{12}+7H_2O+CO_2=2(H_3Mg_3AlSi_3O_{12}.3H_2O)+K_2CO_3+k.$$

For chlorite:

$$(2)\ 2H_2KMg_3AlSi_3O_{12}+6MgCO_3+7H_2O=2[H_3Mg_6AlSi_3O_{12}.6(OH)]+K_2CO_3+5CO_2+k.$$

For talc and gibbsite:

$$(3)\ 4H_2KMg_3AlSi_3O_{12}+6H_2O+4CO_2=3H_2Mg_3Si_4O_{12}+4Al(OH)_3+3MgCO_3+K_2CO_3+H_2O+k.$$
$$(4)\ 2H_2KMg_3AlSi_3O_{12}+CO_2+4H_2O=H_2Mg_3Si_4O_{12}+H_4Mg_3Si_2O_9+2Al(OH)_3+K_2CO_3+k.$$

In equations (3) and (4) if diaspore instead of gibbsite were produced less water would be needed.

Disregarding the carbonates, the increase in volume for hydrophlogopite, equation (1), is 26.89 per cent; for chlorite, equation (2), is 41.02 per cent. The decrease for talc and gibbsite, equation (3), is 7.79 per cent, and for talc and diaspore 18.27 per cent. The increase in volume of the serpentine, talc, and gibbsite, equation (4), is 5.23 per cent.

All of these reactions are those of hydration and solution. They are characteristic of the zone of katamorphism.

According to Clarke, penninite, one of the chlorites, is composed of one molecule of biotite-chlorite and one molecule of phlogopite-chlorite; and clinochlore is composed of two molecules of biotite-chlorite and one molecule of phlogopite-chlorite. It is therefore easy to combine the equation given under biotite for the production of chlorite with the one under phlogopite producing chlorite, and thus produce penninite (pseudorhombohedral and monoclinic; sp. gr. 2.6–2.85) and clinochlore (monoclinic; sp. gr. 2–2.5). However, as the alterations for the production of chlorite from biotite and of chlorite from phlogopite, reactions of hydration, carbonation, and liberation of heat occur in the zone of katamorphism, it may be said that where penninite and clinochlore are produced from biotite and phlogopite the physical-chemical reactions are of the same class as those which have been given for hydrobiotite and hydrophlogopite.

CLINTONITE GROUP.

MARGARITE, CHLORITOID, AND OTTRELITE.

The clintonite group includes the following rock-making minerals:

Margarite:
$H_2CaAl_4Si_2O_{12}$.
Monoclinic.
Sp. gr. 2.99–3.08.

Chloritoid:
$H_2(MgFe)Al_2SiO_7$.
Monoclinic (G) or triclinic (D).
Sp. gr. 3.52–3.57.

Ottrelite:
$H_2(FeMn)Al_2Si_2O_9$.
Monoclinic or triclinic.
Sp. gr. 3.3.

Occurrence.—The most common development of margarite is in connection with corundum. In a number of cases it is recorded that the alumina of the margarite is directly furnished by the corundum. Margarite is also found as a metamorphic mineral in schists and gneisses, associated with the heavy minerals staurolite, tourmaline, etc. As a metamorphic mineral, margarite is also recorded as being derived from diaspore and gibbsite.

Chloritoid and ottrelite both occur in the slates, schists, and gneisses which are derived from the argillaceous sediments as a product of or connected with deep-seated, and especially deep-seated regional metamorphism, and often contact action. They are thus heavy minerals which develop from the simpler constituents in the argillaceous sediments in the zone of anamorphism, their formation resulting in condensation.

Alterations.—The only alteration of the clintonite group recorded is that of margarite to dudleyite. However, as no definite formula for this mineral is given, it is not practicable to write an equation representing the transformation.

While no other alterations of the clintonite group are mentioned, there is no doubt that in the upper zone of metamorphism, especially in the belt of weathering, the chloritoids, ottrelite, and margarite are decomposed into simpler compounds, as are the other silicates.

CHLORITE GROUP.

AMESITE, CORUNDOPHILITE, PROCHLORITE, CLINOCHLORE, AND PENNINITE.

The minerals of the chlorite group, according to Tschermak, may be regarded as isomorphous mixtures of amesite ($H_4Mg_2Al_2SiO_9$) and serpentine ($H_4Mg_3Si_2O_9$) molecules, although Clarke dissents from this conclusion. Tschermak gives the range of the various orthochlorites as follows:

Amesite:	At to At_4Sp.
Corundophilite:	At_4Sp to At_7Sp_3.
Prochlorite (ripidolite):	At_7Sp_3 to At_3Sp_3.
Clinochlore:	At_3Sp_3 to At Sp.
Penninite:	At Sp to At_2Sp_3.

These would correspond to the following compositions:

Amesite:

$H_4Mg_2Al_2SiO_9$ to $H_{20}Mg_{11}Al_8Si_6O_{45}$.
Monoclinic.
Sp. gr. 2.71.

Corundophilite:

$H_{20}Mg_{11}Al_8Si_6O_{45}$ to $H_{40}Mg_{23}Al_{14}Si_{13}O_{90}$.
Monoclinic.
Sp. gr. 2.90.

Prochlorite:
$H_{40}Mg_{23}Al_{14}Si_{13}O_{90}$ to $H_{20}Mg_{12}Al_6Si_7O_{45}$.
Monoclinic.
Sp. gr. 2.78–2.96.

Clinochlore:
$H_{20}Mg_{12}Al_6Si_7O_{45}$ to $H_8Mg_5Al_2Si_3O_{18}$.
Monoclinic.
Sp. gr. 2.65–2.78.

Penninite:
$H_8Mg_5Al_2Si_3O_{18}$ to $H_{20}Mg_{13}Al_4Si_8O_{45}$.
Pseudorhombohedral and monoclinic.
Sp. gr. 2.60–2.85.

A considerable part of the magnesium, as shown by the analyses, may be replaced by iron, the analyses of corundophilite showing as high as 15 per cent of monoxide of iron; of prochlorite, from 15 to 25 per cent, running even higher than the magnesia. The percentage of monoxide of iron in clinochlore and penninite is usually much less. The alumina may be replaced in part by sesquioxide of iron, although the proportion of this replacement is not nearly so great as that of the magnesia by the iron monoxide, the iron sesquioxide generally not running beyond 2 or 3 per cent.

It is apparent that the specific gravities of the chlorites do not regularly grade from lower to higher, as in the feldspars. Doubtless such a regular gradation would occur provided the chlorites were pure magnesium minerals, corresponding to the formulæ above given. The high specific gravities which the intermediate minerals in the group, corundophilite and prochlorite, may have are doubtless explained by their frequent high content of iron monoxide.

Occurrence.—Chlorite is the most abundant and widespread of all the secondary silicates. As a secondary mineral it is probably subordinate only to quartz. Chlorite is nowhere known as a pyrogenic constituent of igneous rock. It is very abundant in many of the altered igneous rocks, both plutonic and volcanic, including lavas and tuffs, being especially abundant in the so-called green-schists. Also it is very abundant in many amphibolites. In the altered igneous rocks which are changed under mass-static conditions it is one of the most abundant secondary constituents, being especially prevalent in the basic rocks, such as the greenstones. It is also found in the acid rocks. Chlorite occurs as a plentiful allogenic constituent in all kinds of mechanical sedimentary rocks. It develops as a

very abundant secondary constituent in the metamorphosed sedimentary rocks, such as slates, schists, and gneisses. Frequently chlorite may occur more abundantly adjacent to intrusive rocks than elsewhere. The most characteristic associated secondary minerals are epidote, serpentine, talc, zeolites, kaolin, magnesite, iron oxides, aluminum oxides, etc.

In the discussion of the individual minerals it has been shown that chlorite is one of the abundant derivation products of the following minerals: Almandite, augite, garnet, hornblende, iolite, prehnite, pyrope, staurolite, tourmaline, and vesuvianite. Being essentially a magnesium-aluminum silicate, it is especially likely to be derived from the heavily magnesian minerals, of which the olivine, pyroxene, amphibole, mica, and garnet groups are the more important. As already seen, corundophilite and prochlorite may contain a large percentage of iron monoxide, and therefore one would naturally expect these chlorites to form from the minerals which also contain a large percentage of iron monoxide, as, for instance, olivine, actinolite, etc. In many cases the mineral from which the chlorite is derived does not contain a sufficient amount of magnesium. In such cases this substance is derived from adjacent minerals, or is brought in in solution. It has been supposed in such cases that the magnesium is transported as a carbonate. However, the principles of its development would be in no way changed if any other salt of magnesium, such as magnesium chloride, were substituted for the carbonate.

In the discussion of the individual minerals it is shown that chlorite develops especially in the upper physical-chemical zone, and particularly in the belt of cementation. Under conditions of quiescence it develops at very considerable depth; but in proportion as interior movement occurs it is likely to develop in smaller quantity or not at all, its place as a metamorphic mineral being taken by the magnesian mica biotite.

Alterations.—The alterations of chlorite, like those of other minerals, are largely dependent upon the zones or belts in which the mineral is located. The only definite alteration products of chlorite which are recorded are those which Tschermak has called enophite and berlanite. The first is said by him to be a serpentinous variety of chlorite. No formula for either has been determined, and therefore it is not possible to write equations representing the transformation. Rosenbusch says that the last stage of the alteration of chlorite is into an aggregate of limonite, carbonate, and quartz. This degeneration is especially characteristic of the belt of weathering. As

usual, no attempt is made to write equations for these degenerative changes; but if one knew definitely the composition of the original mineral and that of the minerals which were produced in a given case, it would be easy to write equations for the change and to calculate the volume relations.

While the alterations of chlorite in the zone of anamorphism are not recorded, it is certain that the chlorite of chloritic rocks under the conditions of the lower physical-chemical zone pass into other constituents, since chlorite is almost always rare or absent in both the sedimentary and the igneous rocks which have recrystallized in the lower zone and have not been later affected by changes in the upper zone.

Therefore in the lower zone chlorite and some of the material of the associated minerals recombine and reproduce minerals from which chlorite was originally derived, or other minerals. There is little doubt that chlorite furnishes a considerable part of the elements for such minerals as the micas, feldspars, amphiboles, pyroxenes, and even the olivines, which develop in the zone of anamorphism, and also it is probable that the chlorite furnishes a part of the constituents for certain of the heavy metamorphic minerals, such as garnet, clintonite, staurolite, tourmaline, etc.

SERPENTINE-TALC GROUP.

SERPENTINE AND TALC.

The serpentine-talc group includes:

Serpentine:

$H_4Mg_3Si_2O_9$. (A part of the Mg may be replaced by Fe, and where the amount of Fe is considerable this mineral is called bastite.)

Monoclinic.

Sp. gr. 2.50–2.65.

Talc:

$H_2Mg_3Si_4O_{12}$.

Orthorhombic or monoclinic.

Sp. gr. 2.7–2.8.

Serpentine and talc, like chlorite, are both hydrous magnesium silicates. Indeed, as has been pointed out, Tschermak regards the serpentine molecule with the amesite molecule ($H_4Mg_2Al_2SiO_9$) in variable proportions to constitute the chlorites. Serpentine is more hydrous and more basic than talc. Since the serpentine molecule is similar to some of the chlorites, one would expect that the occurrence of the two would be very similar, and such is the fact.

SERPENTINE.

Occurrence.—Serpentine occurs in substantially all the varieties of rocks in which chlorite is found, but it is most abundant as a secondary constituent in the igneous rocks which are very heavily magnesian, especially the pyroxenites, peridotites, and similar rocks. Locally it may be so abundant as a secondary constituent in rocks of this class, especially those bearing olivine, as to form serpentine rocks. Serpentine develops very abundantly in the sedimentary rocks which are rich in magnesian constituents, both in detrital material from basic igneous rocks, and in limestones, and in various transition varieties. Serpentine is a product of the zone of katamorphism, including both the belt of cementation and the belt of weathering.

As shown under the discussion of the various minerals, it is secondary to actinolite, biotite, bronzite, chondrodite, clinohumite, diopside, enstatite, hornblende, humite, hypersthene, muscovite, olivine, pyrope, sahlite, and spinel. Of these the most important is olivine, and of second importance are the pyroxenes and amphiboles. In many cases the constituents out of which serpentine is formed are derived not from a single mineral, but from various minerals, in which case the serpentine may replace nonmagnesian minerals, as feldspar, or may form in veins.

Alterations.—Serpentine, where long exposed to the conditions of the belt of weathering, is likely to break up into various minerals, of which brucite (rhombohedral; sp. gr. 2.39), magnesite (rhombohedral; sp. gr. 3.06), opal (amorphous; sp. gr. 2.15), and quartz (rhombohedral; sp. gr. 2.6535) are the more important. By hydration and loss of magnesia it passes into webskyite (amorphous; sp. gr. 1.771).

The reaction by which serpentine passes into magnesite, brucite, and quartz may be written thus:

(1) $H_4Mg_3Si_2O_9+CO_2=MgCO_3+2Mg(OH)_2+2SiO_2+k.$

The increase in volume is 13.02 per cent. In case opal or hydromagnesite were formed the increase in volume would be somewhat greater, and the reaction would involve hydration as well as carbonation. It is of course possible that both brucite and magnesite may not always be formed simultaneously. If brucite and not magnesite be formed the equation is—

(2) $H_4Mg_3Si_2O_9+H_2O=3Mg(OH)_2+2SiO_2+k.$

The volume of the brucite and quartz is 9.82 per cent greater than the serpentine. If magnesite and not brucite be formed the equation is—

(3) $H_4Mg_3Si_2O_9+3CO_2=3MgCO_3+2SiO_2+2H_2O+k.$

The volume of the magnesite and quartz is 18.84 per cent greater than that of the serpentine.

Brauns[a] gives the formula for the development of webskyite as follows:

(4) $3(H_4R_3Si_2O_9)—RO+12aq.=2(H_6R_4Si_3O_{13}+6aq.)$

Where serpentine contains iron as a base, partly replacing the magnesium, the iron is oxidized and may be hydrated, thus producing hematite or limonite.

The breaking up of serpentine occurs especially in the belt of weathering, the transformation representing one of the final changes in the degeneration of the silicates. Alterations of serpentine in the zone of anamorphism are not recorded. But the general absence of serpentine in the schists and gneisses of sedimentary origin profoundly metamorphosed in the zone of anamorphism is conclusive evidence that the serpentine which once was in these rocks, and the associated secondary minerals, have recombined to produce heavy minerals of the classes from which serpentine and those other secondary minerals were originally produced. One could readily form equations for such alterations by reading the equations by which serpentine is formed from right to left. (See Table C, pp. 375–394.)

TALC.

Occurrence.—Talc is practically coextensive in its occurrence with chlorite and serpentine, but in its distribution is more nearly allied to serpentine than to chlorite. Therefore it is found in almost every variety of rock long subjected to alterations in the belt of weathering; but it is especially abundant in the heavily magnesian rocks. Steatite, which is nearly pure talc, is usually derived from the pyroxenites or peridotites. However, talc is so abundant in many schists as to give them the name talcose, or even talc-schists. Also, like serpentine, it occurs abundantly in the dolomite-bearing rocks and in dolomite.

[a] Brauns, R., Studien über den Palaeopikrit von Amelose bei Biedenkopf und dessen Umwandlungsprodukte: Neues Jahrbuch, supp.-vol. 5, Stuttgart, 1887, p. 322.

Talc forms in the upper zone of metamorphism. In this respect it is like chlorite and serpentine. It is especially likely to form under conditions of weathering. The minerals from which talc is derived are as follows: Actinolite, andalusite, anthophyllite, bronzite, cyanite, diopside, enstatite, gehlenite, hypersthene, muscovite, olivine, phlogopite, pyrope, sahlite, scapolites, sillimanite, spinel, staurolite, topaz, and tremolite. The manner of formation is given under the various minerals. Of these minerals the more important are the nonaluminous amphiboles and pyroxenes, both orthorhombic and monoclinic. It also forms rather abundantly from olivine, mica, and garnet.

Alterations.—Alterations of talc are not recorded. It appears to be one of the end products of rock alteration in the belt of weathering. However, I have no doubt that when the talc-bearing rocks are buried so deeply as to pass into the zone of anamorphism and there alteration takes place, talc, like chlorite, serpentine, and other minerals, is destroyed, and that from it alone, or from it and other minerals, the classes of heavy minerals from which the talc was originally produced are again formed.

GLAUCONITE.

Glauconite:

Essentially a hydrous silicate of iron and potassium. Definite formula unknown. The potassium ranges from 1.85 to 6.56 per cent.

Amorphous.

Sp. gr. 2.2–2.4.

Occurrence.—Glauconite occurs in sediments of many kinds and ages. Where it is so abundant as to give the rock a green color it is known as greensand. Greensands are especially prevalent in the Cretaceous.

Alterations.—Since no definite formula for glauconite can be given it is impracticable to write equations representing the transformations. But since glauconite is almost, if not quite, unknown in the schists and gneisses formed in the zone of anamorphism it seems certain that under the conditions of that zone the glauconite is broken up, its constituents passing into other minerals.

KAOLIN GROUP.

Kaolinite is the only important rock-making mineral of this group.

Kaolinite:
$H_4 Al_2 Si_2 O_9$.
Monoclinic.
Sp. gr. 2.6–2.63.

Occurrence.—Kaolinite is a secondary product in all classes of igneous rocks and occurs as an important constituent in all sedimentary rocks except the pure sandstones and the pure limestones. Kaolinite and quartz are the chief constituents of the clays, and kaolinite is a very abundant constituent of muds and grits.

Kaolinite is a product which forms extensively in the zone of katamorphism in the belt of cementation and in the belt of weathering. It is likely to be produced as a result of the decomposition of any of the aluminous minerals. It has been noted as having been produced from the following minerals: Andalusite, anorthoclase, biotite, cyanite, epidote, leucite, microcline, nephelite, orthoclase, plagioclases, scapolites, sillimanite, sodalite, topaz, and zoisite. Of these, undoubtedly the most important are the feldspars, and especially the acid feldspars.

Alterations.—No alterations of kaolinite are recorded. It is certain, however, that where the kaolin-bearing sediments are deeply buried the mineral becomes dehydrated, that such bases as the alkalies and alkaline earths and iron replace the hydrogen, and that various anhydrous silicates or silicates low in hydrogen are produced. It is certain that in the zone of anamorphism the minerals which in the upper physical-chemical zone have broken up into kaolinite as one of the products may recombine to a large extent and reproduce the original minerals.

SUMMARY OF ALTERATION OF SILICATES.

While the important groups of the rock-forming silicates have been treated separately, it may be well in closing the section to class together the groups of the original minerals which have a somewhat similar chemical composition and therefore alter into somewhat similar products.

These classes are called by the petrographers (1) the feldspathoid class, (2) the transition class, and (3) the ferromagnesian class. The feldspathoid class includes the feldspar, nephelite, sodalite, leucite, and wernerite groups. The only rock-forming minerals belonging to the

transition class are those of the muscovite group. The ferromagnesian class includes the pyroxene, amphibole, chrysolite, biotite-phlogopite, and clintonite groups.

(1) In the upper physical-chemical zone, that of katamorphism, the more common alteration products of the feldspathoid class are the kaolins, the zeolites, the epidotes (including both zoisite and epidote proper), diaspore, gibbsite, and quartz. Probably all of these minerals form in both belts of the zone, but the development of the zeolites and the epidotes is more characteristic of the belt of cementation than of the belt of weathering. Indeed, as pointed out under these minerals, under long-continued conditions of the belt of weathering these minerals break up into carbonates of the alkalies and alkaline earths, hydrous and anhydrous, oxides of aluminum and iron, quartz, and, probably, also kaolin. In the zone of anamorphism the more common alteration products of the feldspathoid class are muscovite (damourite) and scapolite. The nephelite, sodalite, and leucite groups alter into the feldspars.

(2) In the zone of katamorphism muscovite alters into serpentine, talc, and vermiculite (hydromuscovite). In the belt of weathering the serpentine and vermiculite may break up into simpler compounds of the same character as those which form from the zeolites and epidotes.

In the lower physical-chemical zone, that of anamorphism, muscovite is one of the minerals commonly produced, and therefore does not usually alter. But by profound and deep-seated metamorphism, the material of muscovite may pass into the heavy ferromagnesian minerals, such as garnet, staurolite, etc.

(3) The ferromagnesian silicates may be divided into two great divisions—those which are nonaluminous, and those which are aluminous. In the zone of katamorphism the most common alteration products of the nonaluminous ferromagnesian silicates are talc and serpentine. The nonaluminous pyroxenes and amphiboles ordinarily pass into talc; the chrysolites ordinarily pass into serpentine. The transformations in these directions are explained by the fact that the pyroxenes, amphiboles, and talc are metasilicates, while the olivines and serpentines are orthosilicates. The metasilicates naturally pass into metasilicates, and the orthosilicates into orthosilicates. In the zone of katamorphism the heavily aluminous ferromagnesian silicates alter into chlorites and epidotes. The pyroxenes and amphiboles which are not heavily aluminous frequently split up into a com-

bination of chlorite and talc, the aluminous part of the original molecule going to the chlorite and the nonaluminous part into the talc. The development of epidote is largely if not wholly confined to the belt of cementation. But chlorite apparently forms both in the belt of cementation and in the belt of weathering, especially where there is abundant vegetation. Under extreme and long-continued conditions of the belt of weathering the serpentines, chlorites, and epidotes are likely to further degenerate, breaking up into carbonates of the alkalies and alkaline earths, anhydrous or hydrous oxides of aluminum and iron, quartz, and kaolin. Or in the belt of weathering these end products may directly develop from the metasilicates without the serpentines, chlorites, and epidotes as intermediate products. In the zone of anamorphism the pyroxenes change to amphiboles; the pyroxenes and amphiboles both alter to biotite; the olivines change to the amphiboles, anthophyllite, tremolite, and actinolite. The biotite group does not ordinarily alter. But by profound metamorphism the material of the biotites, amphiboles, pyroxenes, etc., may pass into the still heavier class of minerals represented by the garnets, staurolites, etc.

THE TITANATES.

TITANITE AND PEROVSKITE.

As rock-making constituents only two titanates of importance, titanite and perovskite, are here treated, ilmenite being given under the oxides.

Titanite:
$CaTiSiO_5$.
Monoclinic.
Sp. gr. 3.4–3.56.

Perovskite:
$CaTiO_3$.
Isometric or pseudoisometric.
Sp. gr. 4.017–4.039.

TITANITE.

Occurrence.—Titanite occurs as a rather subordinate but widespread mineral as an original pyrogenic constituent of igneous rocks, and also in the schists and gneisses. So far as observed, titanite as a secondary constituent is derived from ilmenite and rutile. These alterations are discussed under those minerals.

Alterations.—Titanite alters into rutile (tetragonal; sp. gr. 4.18–4.25), octahedrite (tetragonal; sp. gr. 3.82–3.95), and perovskite (isometric or pseudoisometric; sp. gr. 4.017–4.039).

Rutile and octahedrite may be supposed to be produced by the following reaction:

(1) $CaTiSiO_5+CO_2=TiO_2+CaCO_3+SiO_2+k.$

The expansion of volume is 39.22 per cent for rutile, provided all of the compounds separate as solids, and 42.07 for octahedrite.

Perovskite may be supposed to be produced by the simple breaking up of titanite, according to the reaction:

(2) $CaTiSiO_5=CaTiO_3+SiO_2$

The expansion of volume is 0.14 per cent provided the silica also separates as a solid.

Information as to the natural conditions under which these changes take place is not obtainable from the papers giving the above minerals as secondary to titanite. From the character of the first change one would expect, however, that it would occur in the zone of katamorphism, and especially in the belt of weathering. Under such conditions there would be a reason for the change, for there carbonation of the silicates, with liberation of heat and with expansion of volume, is the rule. As so frequently indicated before, the freed silica may be taken into solution, and if this occurs the volume is decreased. Under what conditions the second reaction is likely to have taken place I can only conjecture from its nature. I should expect it to occur in the zone of katamorphism.

PEROVSKITE.

Occurrence.—Perovskite occurs as an original constituent in eruptive rocks, and also in the metamorphic rocks, such as the schists and gneisses. As a secondary mineral it has been observed as a product secondary to titanite. It may be suspected that in the schists and gneisses it forms in the zone of anamorphism by the union of rutile and octahedrite or brookite, with calcium carbonate; but this is a pure conjecture, as the details of its formation are not found in literature.

Alterations.—The mineral does not readily alter into other compounds, although it has been observed to alter into an undetermined substance, and it is said to alter into ilmenite (hexagonal-rhombohedral; sp. gr. 4.75).

THE PHOSPHATES.

APATITE.

The only important rock-making mineral among the phosphates is apatite.

Apatite:
$CaF.Ca_4P_3O_{12}$, or $CaCl.Ca_4P_3O_{12}$, or a mixture of the two.
Hexagonal.
Sp. gr. 3.17–3.23.

Occurrence.—Apatite is one of the most widespread, if not the most widespread, of all the subordinate constituents of rocks. It is a common, if not an almost universal, constituent of the plutonic rocks, occurs almost as broadly in the volcanic rocks, and is found in many varieties of unaltered or little altered, sedimentary rocks, such as limestones, shales, sandstones, etc.; and, finally, it is almost everywhere found in the metamorphosed igneous and sedimentary rocks.

Alterations.—The only alteration which is recorded for apatite is to osteolite, which is reported as having the same composition as apatite, except that there has been a loss of part or all of the fluorine or chlorine.

It is certain, however, that in the belt of weathering of the zone of anamorphism apatite is slowly dissolved. This is shown by comparative analyses of the weathered with the unweathered varieties of the same rock. This fact has been frequently noted in reference to the iron ores, because here the presence or absence of phosphorus is of such great importance. It may be stated that in the iron ores it is the general rule that those parts of deposits which have been long subjected to weathering bear a smaller proportion of apatite than the continuations of these same deposits in the belt of cementation.

The depletion of the surface rocks in apatite would seem to furnish an adequate source for the apatite in veins, this mineral being taken into solution near the surface and redeposited deeper down, thus being transported from the belt of weathering to the belt of cementation.

THE SULPHATES.

ANHYDRITE AND GYPSUM.

The only important rock-making sulphates are anhydrite and gypsum.

Anhydrite:
$CaSO_4$
Orthorhombic.
Sp. gr. 2.899–2.985.

Gypsum:
$CaSO_4 .2H_2O$
Monoclinic.
Sp. gr. 2.314–2.328.

ANHYDRITE.

Occurrence.—As explained below, the main source of anhydrite is by the alteration of gypsum in the zone of anamorphism. Although I do not know the facts, I conjecture that the anhydrite deposits of Switzerland have had such a history.

Alterations.—The chief alteration of anhydrite is to gypsum (monoclinic; sp. gr. 2.314–2.328). The reaction is:

(1) $CaSO_4+2H_2O=CaSO_4.2H_2O+k$

The increase in volume is 60.30 per cent. This alteration is one which takes place in the zone of katamorphism. An interesting case is that of Bex, Switzerland, where the transformation from anhydrite to gypsum has taken place completely to a depth of from 18 to 30 meters, and where below this depth the material is anhydrite. The change of anhydrite to gypsum is with liberation of heat, expansion of volume, hydration, lowering of specific gravity, and lessening of symmetry, and thus stands as a rare example of all the tendencies of the upper physical-chemical zone.

GYPSUM.

Occurrence.—The most important source of gypsum is as a chemical precipitate, especially in salt lakes having no outlets. It therefore naturally occurs in association with halite, calcite, and mechanical detritus. Gypsum also is produced in a subordinate way through fumarole action. The calcium sulphate for the gypsum in either case is produced by the reaction of sulphuric acid or sulphates upon calcium-bearing salts. Com-

monly the sulphate is formed by the oxidation of a sulphide. A common method is the production of iron sulphate by oxidation of pyrite, marcasite, or pyrrhotite, which reacts upon calcium carbonate, thus producing gypsum. The reaction is—

$$CaCO_3+FeSO_4+2H_2O=CaSO_4.2H_2O+FeCO_3+k.$$

The development of gypsum by this method is illustrated at many mines. Finally gypsum may be formed by the hydration of anhydrite. All these methods of formation of gypsum are characteristic of the zone of katamorphism, and especially of the belt of weathering.

Alterations.—An important alteration of gypsum is to anhydrite (orthorhombic, sp. gr. 2.899–2.985). The reaction is—

$$(1)\quad CaSO_4.2H_2O=CaSO_4+2H_2O-K.$$

The decrease in volume is 37.62 per cent. The other important alteration of gypsum is into calcite (rhombohedral, sp. gr. 2.713–2.714). The reaction is—

$$(2)\quad CaSO_4.2H_2O+CO_2=CaCO_3+H_2SO_4+H_2O+k.$$

The H_2SO_4 produced may simultaneously react upon some other compound. The decrease in volume is 50.29 per cent.

Unless beds of gypsum have been deeply buried the alteration to anhydrite has not extensively occurred. It is a reaction of diminution of volume, absorption of heat, dehydration, increase in specific gravity, and increase in symmetry, and therefore is one of the very rare cases which illustrate all the tendencies of the lower physical-chemical zone. The change of gypsum to calcite is a reaction with liberation of heat and condensation of volume. The change takes place near the surface, especially in the belt of weathering, where carbon dioxide is abundant, and may also occur in the lower zone. It therefore stands, in its physical-chemical relations, in the same position as dolomitization. (See p. 240.)

SECTION 4.—GENERAL STATEMENTS.

PHYSICAL-CHEMICAL FACTORS ON WHICH NATURE OF ALTERATIONS DEPENDS.

As inferences from the foregoing treatment it may be said that the more important physical-chemical factors on which the alteration of an individual mineral depends are (1) the chemical composition of the mineral, (2) the chemical composition of the adjacent minerals, (3) the chemical composition of the circulating solutions, (4) the specific gravity, (5) the symmetry, (6) the heat effect of the reaction, and (7) the pressure and volume.

CHEMICAL COMPOSITION.

Certain chemical compounds are stable under a great variety of conditions; others are stable only under certain definite conditions; and thus the chemical composition influences the stability of minerals. As an illustration of minerals which have stability under widely varying conditions may be mentioned quartz, which forms alike from a magma and from water solutions, and also at the surface and at great depth. Nephelite and sodalite are examples of minerals which can exist only under a comparatively narrow range of conditions.

CHEMICAL COMPOSITION OF ADJACENT MINERALS.

It has been seen that mineral particles may react upon one another, either through the medium of contained solutions or by direct rearrangement under the influence of pressure. Therefore, it is clear that the nature of a mineral which is mainly secondary to another mineral is influenced by the chemical compositions of adjacent minerals.

CHEMICAL COMPOSITION OF CIRCULATING SOLUTIONS.

It has already been shown that the secondary minerals are dependent not only upon the adjacent minerals, but upon the material carried by the underground solutions. The amount of such material is dependent upon the vigor of the circulation. As explained on pages 507–518, 655–656, 764–766, the material added or abstracted may be great in the zone of katamorphism, but is usually rather limited in amount in the zone of anamorphism.

SPECIFIC GRAVITY.

Apparently high specific gravity is favorable to stability. This is what one would expect, for high specific gravity involves a comparatively close arrangement of the atoms. Where the atoms are near together the molecular attraction is great, and in order to break up the combination this force must be overcome. This principle is illustrated by dimorphous and trimorphous compounds. Diamond (av. sp. gr. 3.52) is more stable than graphite (av. sp. gr. 2.16), and graphite is more stable than carbon (sp. gr. 1.9, charcoal). Pyrite (av. sp. gr. 5.025) is more stable than marcasite (av. sp. gr. 4.870). Cyanite (av. sp. gr. 3.615) is more stable than sillimanite (av. sp. gr. 3.235), and sillimanite is more stable than andalusite (av. sp. gr. 3.18). Quartz (av. sp. gr. 2.6535) is more stable than tridymite (av. sp. gr. 2.305). This last instance well illustrates the principle; for the symmetry of quartz and tridymite is the same, and this variable factor included in the previous illustrations is excluded. The same is true of andalusite and sillimanite of the aluminum-silicate series. As pointed out on page 112, the more condensed a compound, or, in other words, the higher the specific gravity, the less energy is potentialized. In the change from a lower to a higher specific gravity energy is liberated. In this we have the physical explanation of the greater stability of minerals of high specific gravity. To form minerals of higher specific gravity from those of lower specific gravity releases energy. To reproduce minerals of lower specific gravity from those of higher specific gravity requires the expenditure of energy. An exception to the above rule as to increase of stability with increase of specific gravity is furnished by calcite and aragonite. Calcite (av. sp. gr. 2.7135) is more stable than aragonite (av. sp. gr. 2.94), but in this case the factor of symmetry enters, which is discussed under the next heading.

SYMMETRY.

Apparently the greater the symmetry the more stable is the mineral likely to be. This principle is illustrated by substances which are dimorphous or trimorphous.

Pyrite (isometric) is more stable than marcasite (orthorhombic). Diamond (isometric) is more stable than graphite (hexagonal), and this is more stable than amorphous carbon. Kelvin suggests[a] that soft

[a] Lord Kelvin, Popular lectures and addresses, Macmillan & Co., London, 1894, vol. 2, p. 428.

phosphorus as compared with red phosphorus, and prismatic sulphur as compared with octahedral sulphur, contain potential energy. When the change from the first to the second takes place, energy is evolved, and consequently the second form is more stable. These changes are in the direction of higher symmetry, and Kelvin's argument applies equally well to all the changes in which minerals pass from a lower to a higher degree of symmetry. To reproduce minerals of lower symmetry would require the expenditure of energy. Therefore we have an energy cause why minerals with high symmetry are more stable. They contain less potential energy. Their formation is under the apparent law of the universe of dissipation of energy.

SPECIFIC GRAVITY AND SYMMETRY.

Where specific gravity and symmetry work together, as in a number of the illustrations mentioned, there seem to be no exceptions to the rule of increase of stability with increase of specific gravity and increase in symmetry.

But in those instances in which the specific gravity and symmetry are opposed to each other it can not be predicted which will be the dominant factor. For instance, calcium carbonate crystallizes as calcite (hexagonal-rhombohedral; sp. gr. 2.7135) and aragonite (orthorhombic; sp. gr. 2.94). The former is the more stable. In this case it seems that symmetry is the dominant factor. In the aluminum silicate which crystallizes as andalusite (orthorhombic; sp. gr. 3.18), sillimanite (orthorhombic; sp. gr. 3.235), and cyanite (triclinic; sp. gr. 3.615), the latter is the most stable. In this case it appears that the specific gravity is the determining factor.

It is believed that when the energy relations of these changes become known it will be found that in each of these cases the more stable molecules contain less potential energy. If this be true, calcite, considering both its specific gravity and its symmetry, contains less energy than aragonite, and cyanite less than andalusite or sillimanite. If this conjecture be true, all compounds are subject to a common law. That mineral forming from a compound is most stable in which the minimum energy is contained.

The relations of symmetry and specific gravity raise some very interesting questions as to the arrangement of the molecules in minerals. Pressure undoubtedly tends to produce the most compact arrangement.

(See pp. 182–186.) According to Slichter, the most compact possible arrangement of spherical molecules is that which gives a rhombohedral unit having face angles equal to 60° and 120°.[a] One might therefore conclude, other things being equal, that minerals having hexagonal crystallization would be those which have the closest arrangement of molecules and therefore the highest specific gravity; but plainly there are other factors entering into the problem, for, as already pointed out, aragonite (orthorhombic) has a higher specific gravity than calcite (hexagonal), and cyanite (triclinic) has a higher specific gravity than sillimanite and andalusite (orthorhombic). On the other hand, diamond (isometric) has a higher specific gravity than graphite (hexagonal). This is an especially interesting case, since the cubical arrangement of molecules, the one ordinarily appealed to to explain isometric symmetry, is the most open of all possible arrangements. From the foregoing it appears perfectly clear that besides the manner of the arrangement of the molecular particles the distance of the molecules from one another enters as a very important factor. Also the shape of the molecules, the closeness of the arrangement of their atoms, and the complexity of the molecules themselves doubtless enter as important factors into the density of minerals.

HEAT REACTIONS.

Other things being equal, within the lithosphere reactions take place which give the greatest liberation of heat. This law is best illustrated at or near the surface, where the reactions usually occur in accordance with it. The reactions of oxidation, hydration, and carbonation are therefore dominant. However, the law of reactions with liberation of heat becomes less and less able to control as the pressure becomes considerable. Where the pressure is great, as noted under the next heading, it determines the reaction without respect to whether heat is absorbed or liberated, and in many cases the reactions take place with the absorption of heat, so far as the chemical factors are concerned. If all the physical factors also were included, all reactions would take place with the dissipation of energy. (See p. 57.)

[a] Slichter, C. S., Theoretical investigation of the motion of ground waters: Nineteenth Ann. Rept. U. S. Geol. Survey, pt. 2, 1899, pp. 306–310.

PRESSURE AND VOLUME.

Pressure lessens the volume and therefore tends to preserve and to produce minerals which have a high specific gravity. Where the pressure is small this factor is relatively inefficient and consequently other factors usually control, and many minerals of low specific gravity form. But even where the pressure is small it is not unimportant, at least retarding reactions which would otherwise occur. This is illustrated by a partially altered rock described by Merrill,[a] which seemed solid when confined by the surrounding rock, but which when brought to the surface from a depth of a few feet, and thus freed from pressure, rapidly decomposed and disintegrated. Where the pressure is great it is likely to be a determinative force, controlling the reactions. At the depths of the zone of anamorphism the uniform production of anhydrous or slightly hydrous minerals of higher average specific gravity than those formed in the zone of katamorphism is clear evidence of the dominance of pressure.

In this connection it will be well to mention the mineral groups, with their specific gravities, which are more characteristic of the zones of katamorphism and anamorphism.

The characteristic products of the zone of katamorphism are: Of the oxides, (1) those of silicon, opal, chalcedony, and quartz (sp. gr. 2.1 to 2.654); (2) those of iron, including the hydrous and anhydrous ferric-oxides (sp. gr. 3.80 to 5.225); (3) the hydrous aluminum oxides, gibbsite and diaspore (sp. gr. 2.35 and 3.40); of the carbonates, calcite and dolomite (sp. gr. 2.7135 and 2.85); of the silicates, (1) the epidote-zoisite group (sp. gr. 3.25 to 4.20); (2) zeolite group (sp. gr. 2.04 to 2.40); (3) chlorite group (sp. gr. 2.60 to 2.96); (4) serpentine-talc group (sp. gr. 2.50 to 2.80); and kaolin group (sp. gr. 2.6 to 2.63). (See pp. 519–520, 621–627.)

The characteristic important mineral groups formed in the zone of anamorphism are as follows: Of the sulphides, pyrite, and pyrrhotite (sp. gr. 5.025 and 4.61); of the oxides, (1) those of silicon, chert, chalcedony, and quartz (sp. gr. 2.6 to 2.654); (2) those of iron, hematite, magnetite, and ilmenite (sp. gr. 5.225, 5.174, and 4.75); (3) those of aluminum, corundum (sp. gr. 4.025); (4) those of titanium, rutile, octahedrite, and brookite (sp. gr. 4.215, 3.885, and 3.975); of the silicates, (1) the feldspar group (sp. gr.

[a] Merrill, George P., Rocks, rock weathering, and soils, Macmillan Co., New York, 1897, pp. 252–253.

2.54 to 2.76); (2) pyroxene group (sp. gr. 2.68 to 3.58); (3) amphibole group (sp. gr. 2.9 to 3.713); (4) garnet group (sp. gr. 3.41 to 4.30); (5) chrysolite group (sp. gr. 3.2 to 4.1); (6) scapolite group (sp. gr. 2.566 to 2.74); (7) aluminum silicate group (sp. gr. 3.16 to 3.67); (8) humite group (sp. gr. 3.1 to 3.2); (9) tourmaline (sp. gr. 3.09); (10) staurolite (sp. gr. 3.71); (11) mica group (sp. gr. 2.7 to 3.1); (12) clintonite group (sp. gr. 2.9 to 3.57).

The average specific gravity of the mineral groups above mentioned as products of the zone of katamorphism is 2.948. The average specific gravity of the mineral groups of the zone of anamorphism is 3.488. It thus appears that the average specific gravity of the minerals which develop in the zone of anamorphism is 18 per cent greater than that of the minerals in the zone of katamorphism. This comparison is of course very roughly approximate, since the various minerals are not present in equal quantities. Probably the percentage is too great, since the heavy sulphides and the very heavy silicates are given equal weight with the abundant but lighter quartz, feldspars, pyroxenes, amphiboles, and micas. The comparison, however, shows beyond question that a given mass of material occupies much less space in the lower physical-chemical zone than in the upper physical-chemical zone.

It is shown under the next heading that many of the reactions written for the minerals of the zone of katamorphism may be read in reverse order when the resultant minerals are buried so deep as to be in the zone of anamorphism. The lighter minerals characteristic of the zone of katamorphism reunite to produce heavier minerals of the zone of anamorphism, such as the feldspars, the micas, the pyroxenes, the amphiboles, the chrysolites, andalusite, etc. Furthermore, where the pressure is great enough these minerals rearrange themselves again in whole or in part so as to produce still heavier minerals, such as garnet, staurolite, tourmaline, sillimanite, cyanite, etc. This great change takes place within the narrow range of less than 10,000 meters.

Since in this mere outer film of the earth a great diminution in the volume of the minerals has taken place, it is thought to be highly probable that, even if the average chemical composition of the interior of the earth be supposed to be the same as the crust, the pressure is such that the minerals may further rearrange themselves into still more compact products, thus probably producing minerals of a different kind and higher specific

gravity than any with which we are acquainted. Indeed, the interior pressures increase so rapidly with depth that rearrangement might occur again and again. Therefore, even if the average chemical composition be the same deep within the earth as at the surface, in the centrosphere, in consequence of high pressure, there may be a set of silicate minerals which have as high a specific gravity as the average density of the earth, viz, 5.67. If the accepted theory as to the distance between molecules be correct, viz, that molecules of ordinary liquids at the surface of the earth do not occupy more than one-third of the total volume,[a] there is ample room between them for the condensed rearrangement suggested. From the foregoing it appears that we do not necessarily appeal to a great preponderance of heavy metals deep within the earth to explain its average high specific gravity. It may be very largely explained by the condensation of the material due to pressure. If, as suggested by Chamberlin, the average specific gravity of the material of the earth be that of meteoric falls, the average change in specific gravity would be from 3.69 to 5.67 as a result of pressure. The great increase in the average specific gravity of minerals with increase of pressure in the crust of the earth would seem to make the estimate of the change in average specific gravity of the minerals from 3.69 to 5.67, as a result of the very great pressures deep within the earth, a very modest one.

While I have no doubt that the condensation of the earth material into heavier compounds as a result of pressure is a partial explanation of the high specific gravity of the earth, I by no means urge this as the sole cause. Indeed, it is probable that the segregation of heavy material toward the center and lighter material toward the surface has steadily continued throughout geological time, and therefore the difference in composition is a very important factor in the difference in density at the surface and the center. But I do not venture even a guess as to the relative importance of the two factors of condensed compounds and segregation of material in explaining the increase in density of the material of the earth with increase of depth.

[a] Nernst, W., Theoretical chemistry, trans. by C. S. Palmer, Macmillan & Co., London, 1895, p. 196.

REVERSIBLE REACTIONS.

On the foregoing pages numerous reactions have been written by which the minerals characteristic of the zone of katamorphism are produced; very few reactions have been written by which the minerals of the zone of anamorphism are reproduced. It is certain that when the minerals formed in the belts of weathering and cementation are altered under the conditions of the zone of anamorphism the minerals characteristic of that zone develop; therefore it is believed that many of the reactions for the development of the minerals of the zone of katamorphism are reversible. To illustrate, in the zone of katamorphism olivine may alter into the minerals serpentine, magnetite, magnesite, and quartz, according to the following equation:

$$3Mg_2FeSi_2O_8+3CO_2+4H_2O+O=2H_4Mg_3Si_2O_9+Fe_3O_4+3MgCO_3+2SiO_2+k.$$

It is believed that when these four minerals are brought together in proper proportions under favorable conditions in the deep-seated zone the reverse reaction occurs, and that the equation may be read from right to left instead of left to right, thus reproducing the olivine.

The above illustration is chosen because the change from left to right involves carbonation, desilication, hydration, and oxidation; and the change from right to left involves silication, decarbonation, dehydration, and deoxidation. Of course, where deoxidation takes place in the zone of anamorphism some reducing agent must be present to utilize the abstracted oxygen. The principle of the reversibility of the reactions in the two opposing zones is actually illustrated in a few cases where the products of the zone of katamorphism have been observed to alter in the zone of anamorphism. For instance, it is recorded (p. 261) that analcite is derived from albite according to the following equation:

$$2NaAlSi_3O_8+2H_2O=Na_2Al_2Si_4O_{12}.2H_2O+2SiO_2+k;$$

whereas we find (p. 334) that analcite alters to albite by the reaction:

$$Na_2Al_2Si_4O_{12}.2H_2O+2SiO_2=2NaAlSi_3O_8+2H_2O-k.$$

In other words, the reaction is exactly reversible; for while the k is plus in the first equation and minus in the second, it is on opposite sides in the two equations. The feldspars alter into many zeolites, and a number of

the zeolites alter into the various feldspars. The above reaction chances to be the only one given for these groups which is exactly reversed. This is a consequence of the fact that reactions are written only for *recorded* alterations. There can be no doubt that practically all the equations representing the recorded alterations of the feldspars (pp. 261–263) into the zeolites, and all the reactions representing the recorded alterations of the zeolites (pp. 333–334) into the feldspars, are reversible. For instance, we have anorthite altering into gismondite as follows (p. 262):

$$3CaAl_2Si_2O_8+12H_2O=Ca_3Al_6Si_6O_{24}.12H_2O+k.$$

Can one doubt that if gismondite passes into the zone of anamorphism dehydration may take place and anorthite be reproduced?

Another line of evidence pointing to the reversibility of the reactions in the two zones is the frequent recorded association of corundum with diaspore and gibbsite, the latter minerals being secondary to the corundum. Can it be doubted that these hydrates may be dehydrated in the zone of anamorphism and reproduce corundum? Of course this particular change may not occur alone. At the same time the dehydration takes place the alumina may unite with silica and form andalusite, sillimanite, or cyanite, or the alumina may enter into some other silicate.

Bearing in the same direction are the experiments made by Daubrée upon serpentine.[a] It is well known that both enstatite and olivine alter into serpentine. Daubrée found that by the fusion of serpentine it split up into enstatite and olivine, according to the following equation:

$$H_4Mg_2Si_2O_9+Heat=MgSiO_3+MgSiO_4+2H_2O+k.$$

Finally, my chief reason, in addition to those already given, for belief in the reversibility of the reactions in the two zones lies in the actual compositions of the unmetamorphosed sediments and their metamorphosed equivalents. The unmetamorphosed pelites are composed largely of the lighter hydrous minerals of the belt of weathering and the belt of cementation. It is true that with these, as already explained, there are also considerable, or even dominant, quantities of residual undecomposed anhydrous minerals; but it is certain that the metamorphosed equivalents of these pelites contain none of the minerals which are characteristic of

[a] Daubrée, A., Expériences synthétiques relatives aux météorites: Comptes rendus des séances de l'académie des sciences, vol. 62, Paris, 1866, p. 661.

the belts of weathering and cementation, and the only possible conclusion is that these minerals have recombined and reproduced the heavier minerals of the lower physical-chemical zone. That this is so is shown by the fact that, barring the water and the carbon dioxide which are liberated in the process of alteration, the average chemical compositions of the unaltered pelites and their metamorphosed equivalents are nearly the same.

While it is held that the reactions are reversible, it is not supposed that this is often exactly the case for a given rock. In order that this should even approximately take place, it would be necessary that there be no change of average composition in the zone of katamorphism, and this is never the case. The minerals formed in the zone of anamorphism depend not only upon the minerals of the zone of katamorphism present, but upon their proportion and many other factors. What is meant by the reversibility of the reactions is that, when compounds produced in the zone of katamorphism from a given mineral are together in proper proportions and conditions in the zone of anamorphism, the original mineral may be reproduced.

If this law of the reversibility of reactions in the two zones be true, the question naturally arises why so few of the reversing reactions in the zone of anamorphism have been recorded. The answer lies in the difference in the readiness with which observations may be made in the two zones. The reactions of the belts of weathering and cementation of the zone of katamorphism have been more fully described, because they are constantly taking place at or near the surface under conditions of ready observation. Many of the reverse reactions have not been fully described, because they occur at depth, and because in areas of strong metamorphic action they have been complete. Usually gradation from practically complete reactions to very incomplete reactions in the zone of anamorphism is comparatively rapid. But notwithstanding the very imperfect observations of the zone of anamorphism, the general reversibility of the reactions in the two zones seems as certain as if it were established by observation, and it is believed that it will be established by observation.

If the conclusions of the foregoing paragraphs be correct it is evident that there is an almost entirely neglected field of observation in metamorphism—that by which the minerals of the zone of anamorphism are produced from the minerals of the zone of katamorphism.

For the reasons given above, I conclude: *It is believed that most of the equations which represent the reactions in the zone of katamorphism are reversible in the zone of anamorphism; and so far as there is expansion of volume and liberation of heat in the upper zone, just so far is there condensation of volume and absorption of heat in the lower zone.*

SECTION 5. TABLES.

In order to present compactly the essential facts as to the alterations of each mineral, a set of tables is here given.

Table A gives the mineral sources of each of the minerals.

Table B gives the minerals to which each mineral alters.

Table C gives the equations representing the alterations of each of the minerals into other minerals and shows the volume changes.

Table D classifies the alterations of the minerals under processes and gives their various combinations, with volume changes.

TABLE A.—*Sources of minerals.*

Acmite is derived from	arfvedsonite.
Actinolite is derived from	ankerite, bronzite, hypersthene, olivine, parankerite, sahlite.
Albite is derived from	analcite, heulandite, laumontite, plagioclases (with orthoclase), sodalite, spodumene, stilbite.
Allophane is derived from	anorthoclase, microcline, orthoclase.
Amesite is derived from	pyrope.
Analcite is derived from	laumontite, leucite, nephelite, plagioclases, sodalite.
Anhydrite is derived from	gypsum.
Anthophyllite is derived from	bronzite, hypersthene, olivine.
Aphrosiderite is derived from	garnet.
Augite is derived from	hornblende.
Bastite is derived from	actinolite, anthophyllite, bronzite, cummingtonite, hypersthene, sahlite.
Berlanite is derived from	chlorite.
Beta-spodumene is derived from	spodumene.
Biotite is derived from	anorthoclase, augite, hornblende, microcline, orthoclase, scapolites.
Biotite-chlorite is derived	biotite.
Brucite is derived from	chondrodite, clinohumite, humite, serpentine.
Breunerite is derived from	olivine.
Calcite is derived from	actinolite, ankerite, anthophyllite, aragonite, augite, diopside, dolomite, epidote, fluorite, garnet, grossularite, gypsum, haüynite, hornblende, noselite, parankerite, sahlite, scapolites, tremolite, zoisite.
Chabazite is derived from	haüynite, noselite, plagioclases.
Chalcedony is derived from	augite, sahlite.
Chlorite is derived from	almandite, augite, biotite, garnet, hornblende, iolite, phlogopite, prehnite, pyrope, staurolite, tourmaline, vesuvianite.

TABLE A.—*Sources of minerals*—Continued.

Cimolite is derived from.....anorthoclase, microcline, orthoclase.
Chlorophyllite is derived from.....iolite.
Chromite is derived from.....olivine.
Clinochlore is derived from.....biotite (with phlogopite).
Corundum is derived from.....diaspore, gibbsite.
Cyanite is derived from.....andalusite, corundum, diaspore, gibbsite.
Cymatolite is derived from.....spodumene.
Damourite is derived from.....andalusite, corundum, cyanite, microcline, orthoclase, sillimanite, staurolite, topaz.
Diaspore is derived from.....biotite, corundum, garnet (conjectural), gibbsite, haüynite, muscovite, nephelite, noselite, phlogopite, scapolites, sodalite.
Diopside is derived from.....dolomite.
Dolomite is derived from.....ankerite, calcite, parankerite.
Dudleyite is derived from.....margarite.
Enophite is derived from.....chlorite.
Enstatite is derived from.....pyrope.
Epidote is derived from.....anorthoclase, augite, biotite, garnet, hornblende, microcline, orthoclase, plagioclases, scapolites.
Epistilbite is derived from.....plagioclases.
Eucryptite is derived from.....spodumene.
Fassaite is derived from.....gehlenite.
Garnet is derived from.....vesuvianite.
Gibbsite is derived from.....anorthoclase, andalusite, biotite, cancrinite, corundum, cyanite, epidote, garnet (conjectural), haüynite, microcline, muscovite, nephelite, noselite, orthoclase, phlogopite, plagioclases, pyrope, scapolites, sillimanite, sodalite, topaz, tourmaline, zoisite.
Gismondite is derived from.....plagioclases.
Grossularite is derived from.....gehlenite.
Grünerite is derived from.....siderite.
Gypsum is derived from.....anhydrite.
Halloysite is derived from.....anorthoclase, microcline, orthoclase.
Hematite is derived from.....actinolite, ankerite, anthophyllite, biotite, bronzite, garnet, greenalite, grünerite, hornblende, hypersthene, ilmenite, limonite, magnetite, marcasite, olivine, parankerite, pyrite, serpentine, siderite.
Hercynite is derived from.....olivine.
Heulandite is derived from.....plagioclases.
Hornblende is derived from.....augite, garnet.
Hydrobiotite is derived from.....biotite.
Hydromagnesite is derived from.....brucite.
Hydromuscovite is derived from.....nephelite, scapolites, sodalite.
Hydronephelite is derived from.....nephelite, sodalite.
Hydrophlogopite is derived from.....phlogopite.
Hydrotalcite is derived from.....olivine.
Hypersthene is derived from.....almandite, biotite, garnet.
Ilmenite is derived from.....perovskite, rutile.
Kaolin is derived from.....andalusite, anorthoclase, biotite, cyanite, epidote, garnet (conjectural), leucite, microcline, nephelite, orthoclase, the plagioclases, the scapolites, sillimanite, sodalite, topaz, and zoisite.
Laumontite is derived from.....anorthite.

TABLE A.—*Sources of minerals*—Continued.

Lepidomelane is derived from.....arfvedsonite.
Limonite is derived from.....actinolite, ankerite, anthophyllite, arfvedsonite, biotite, bronzite, chlorites, epidote, garnet, greenalite, grünerite, hematite, hornblende, hypersthene, ilmenite, magnetite, marcasite, olivine, parankerite, pyrite, pyrrhotite, serpentine, siderite.
Magnesite is derived from.....garnet, olivine, pyrope, serpentine.
Magnetite is derived from.....actinolite, ankerite, arfvedsonite, augite, biotite, bronzite, diopside, garnet, greenalite, grünerite, hematite, hornblende, hypersthene, ilmenite, marcasite, olivine, parankerite, pyrite, pyrrhotite, sahlite, siderite.
Malacon (hydrous zircon) is derived from.....zircon.
Marcasite is derived from.....hematite.
Margarite is derived from.....corundum, diaspore, gibbsite.
Meionite is derived from.....grossularite.
Mesolite is derived from.....plagioclases.
Mica is derived from.....spinel, tourmaline, vesuvianite.
Microcline is derived from.....spodumene.
Muscovite is derived from.....anorthoclase, diaspore, gibbsite, leucite, microcline, nephelite, orthoclase, plagioclase and orthoclase, scapolites, sodalite, spodumene.

See also Damourite.

Natrolite is derived from.....apatite, chabazite, haüynite, nephelite, noselite, plagioclases, sodalite.
Nephelite is derived from.....leucite, sodalite (conjectural).
Newtonite is derived from.....anorthosite, microcline, orthoclase.
Octahedrite is derived from.....ilmenite, titanite.
Opal is derived from.....olivine, serpentine.
Orthoclase is derived from.....analcite, heulandite, leucite, laumontite, stilbite.
Osteolite is derived from.....apatite.
Paragonite is derived from.....anorthoclase, muscovite, plagioclases.
Pectolite is derived from.....apophyllite.
Penninite is derived from.....biotite (with phlogopite).
Perovskite is derived from.....titanite.
Phillipsite is derived from.....plagioclases.
Phlogopite-chlorite is derived from.....phlogopite.
Pinite is derived from.....iolite.
Prehnite is derived from.....analcite, laumontite, mesolite, natrolite, plagioclases, scolecite.
Pyrite is derived from.....marcasite, pyrrhotite.
Pyrophyllite is derived from.....anorthoclase, microcline, orthoclase.
Quartz is derived from.....actinolite, anorthite, anorthoclase, anthophyllite, augite, biotite, bronzite, chalcedony, chlorites, cummingtonite, diopside, enstatite, epidote, garnet, grossularite, hornblende, hypersthene, microcline, olivine, opal, orthoclase, plagioclases, prehnite, pyrope, sahlite, scapolites, serpentine, tridymite, zoisite.
Rutile is derived from.....brookite, ilmenite, octahedrite, titanite.
Sahlite is derived from.....ankerite, parankerite.
Scapolites are derived from.....plagioclases.
Scolecite is derived from.....plagioclases.
Serpentine is derived from.....actinolite, biotite, bronzite, chondrodite, clinohumite, diopside, enstatite, hornblende, humite, hypersthene, muscovite, olivine, pyrope, sahlite, spinel.

TABLE A.—*Sources of minerals*—Continued.

Siderite is derived from.....arfvedsonite, garnet, hematite, hornblende, limonite, magnetite, olivine.
Sillimanite is derived from.....andalusite, biotite, corundum, cyanite, diaspore, gibbsite.
Smaragdite is derived from.....diallage.
Sodalite is derived from.....nephelite.
Spinel is derived from.....almandite, biotite, corundum, diaspore, garnet, gibbsite, olivine, pyrope.
Steatite is derived from.....andalusite, cyanite, muscovite, sillimanite, topaz, tourmaline.
Stilbite is derived from.....haüynite, noselite, plagioclases.
Talc is derived from.....actinolite, andalusite, anthophyllite, bronzite, cyanite, diopside, enstatite, gehlenite, hypersthene, muscovite, olivine, phlogopite, pyrope, sahlite, scapolites, sillimanite, spinel, staurolite, topaz, tremolite.
Titanite is derived from.....ilmenite, rutile.
Thomsonite is derived from.....nephelite, plagioclases, sodalite.
Tremolite is derived from.....diopside, dolomite, olivine.
Vermiculite is derived from.....muscovite.
Webskyite is derived from.....serpentine.
Wollastonite is derived from.....calcite, dolomite.
Zoisite is derived from.....corundum, diaspore, gibbsite, grossularite, plagioclases.

TABLE B.—*Alteration products of minerals.*

Actinolite alters to.....bastite, calcite, hematite, limonite, magnetite, serpentine, talc, quartz.
Albite alters to.....analcite, gibbsite, kaolin, marialite, natrolite, quartz.
Almandite alters to.....chlorite, hypersthene, spinel.
Analcite alters to.....albite, orthoclase, prehnite.
Andalusite alters to.....cyanite, kaolin, gibbsite, muscovite (damourite), sillimanite, talc (steatite).
Anhydrite alters to.....gypsum.
Ankerite alters to.....actinolite, calcite, dolomite, hematite, limonite, magnetite, sahlite.
Anorthite alters to.....gibbsite, gismondite, kaolin, laumontite, meionite, prehnite, quartz, scolecite, thomsonite, zoisite.
Anorthoclase alters to.....allophane, biotite, cimolite, damourite, epidote, gibbsite, halloysite, kaolin, muscovite, newtonite, paragonite, pyrophylite, quartz.
Anthophyllite alters to.....bastite, calcite, hematite, limonite, quartz, talc.
Apatite alters to.....osteolite.
Apophyllite alters to.....pectolite.
Aragonite alters to.....calcite.
Arfvedsonite alters to.....acmite, lepidomelane, limonite, magnetite.
Augite alters to.....biotite, calcite, chalcedony, chlorite, epidote, hornblende, magnetite, quartz.
Beta-spodumene alters to.....albite, eucryptite, muscovite.
Biotite alters to.....chlorite, diaspore, epidote, gibbsite, hematite, hydrobiotite, hypersthene, kaolin, limonite, magnetite, quartz, serpentine, sillimanite, spinel.
Biotite (with phlogopite) alters to.....penninite, clinochlore.
Bronzite alters to.....actinolite, anthophyllite, bastite, hematite, limonite, magnetite, quartz, serpentine, talc.
Brookite alters to.....rutile.
Brucite alters to.....hydromagnesite.

TABLE B.—*Alteration products of minerals*—Continued.

Calcite alters to ..... dolomite, wollastonite.
Cancrinite alters to ..... calcite, gibbsite, natrolite.
Chabazite alters to ..... natrolite.
Chlorite alters to ..... berlanite, enophite, limonite, quartz.
Chondrodite alters to ..... brucite, serpentine.
Clinohumite alters to ..... brucite, serpentine.
Corundum alters to ..... diaspore, cyanite, gibbsite, margarite, muscovite (damourite), sillimanite, spinel, zoisite.
Cummingtonite alters to ..... bastite, quartz.
Cyanite alters to ..... kaolin, gibbsite, muscovite (damourite), talc (steatite).
Diallage alters to ..... calcite, chlorite, epidote, feldspar, magnetite, quartz, smaragdite.
Diaspore alters to ..... corundum, cyanite, margarite, muscovite, sillimanite, spinel, zoisite.
Diopside alters to ..... calcite, magnetite, quartz, serpentine, talc, tremolite.
Dolomite alters to ..... calcite, diopside, tremolite, wollastonite.
Enstatite alters to ..... quartz, serpentine, talc.
Epidote alters to ..... calcite, gibbsite, kaolin, limonite, quartz.
Fluorite alters to ..... calcite.
Garnet alters to ..... aphrosiderite, calcite, chlorite, diaspore (conjectural), epidote, gibbsite (conjectural), hematite, hornblende, hypersthene, iron oxide, kaolin (conjectural), limonite, magnesite, magnetite, quartz, siderite.
Gehlenite alters to ..... fassaite, grossularite, talc.
Gibbsite alters to ..... corundum, cyanite, diaspore, margarite, muscovite, sillimanite, spinel, zoisite.
Grossularite alters to ..... calcite, meionite, quartz, zoisite.
Grünerite alters to ..... hematite, limonite, magnetite.
Gypsum alters to ..... anhydrite, calcite.
Haüynite alters to ..... calcite, chabazite, diaspore, gibbsite, natrolite, stilbite.
Hematite alters to ..... limonite, magnetite, marcasite, pyrite, siderite.
Heulandite alters to ..... albite, orthoclase.
Hornblende alters to ..... augite, biotite, calcite, chlorite, epidote, hematite, magnetite, quartz, serpentine, siderite.
Humite alters to ..... brucite, serpentine.
Hypersthene alters to ..... actinolite, anthophyllite, bastite, hematite, limonite, magnetite, quartz, serpentine, talc.
Ilmenite alters to ..... hematite, limonite, magnetite, octahedrite, rutile, titanite.
Iolite alters to ..... chlorite, chlorophyllite, pinite.
Laumontite alters to ..... albite, analcite, orthoclase, prehnite.
Leucite alters to ..... analcite, kaolinite, muscovite, nephelite, orthoclase.
Limonite alters to ..... hematite, siderite.
Magnetite alters to ..... hematite, limonite, siderite.
Marcasite alters to ..... hematite, limonite, magnetite, pyrite.
Margarite alters to ..... dudleyite.
Marialite alters to ..... biotite, kaolin, muscovite, quartz, talc.
Meionite alters to ..... biotite, calcite, epidote, gibbsite, kaolin, muscovite.
Mesolite alters to ..... prehnite.
Microcline alters to ..... allophane, biotite, cimolite, damourite, epidote, gibbsite, halloysite, kaolin, muscovite, newtonite, pyrophyllite, quartz.
Muscovite alters to ..... diaspore, gibbsite, paragonite, serpentine, talc (steatite), vermiculite.

TABLE B.—*Alteration products of minerals*—Continued.

Natrolite alters to	prehnite.
Nephelite alters to	albite (conjectural), analcite, diaspore, gibbsite, hydromuscovite (pinite), hydronephelite, kaolin, muscovite, natrolite, sodalite, thomsonite.
Noselite alters to	calcite, chabazite, diaspore, gibbsite, natrolite, stilbite.
Octahedrite alters to	rutile.
Olivine alters to	actinolite, anthophyllite, breunnerite, chromite, hematite, hercynite, hydrotalcite, limonite, magnesite, magnetite, opal, quartz, serpentine, siderite, spinel, tremolite.
Opal alters to	chalcedony, chert, quartz.
Orthoclase alters to	allophane, biotite, cimolite, damourite, epidote, gibbsite, halloysite, kaolin, muscovite, newtonite, pyrophyllite, quartz.
Parankerite alters to	actinolite, calcite, dolomite, hematite, limonite, magnetite, sahlite.
Perovskite alters to	ilmenite.
Phlogopite alters to	chlorite, diaspore, gibbsite, hydrophlogopite, talc.
Phlogopite (with biotite) alters to	clinochlore, penninite.
Plagioclases alter to	analcite, chabazite, epidote, epistilbite, gibbsite, gismondite, heulandite, kaolin, laumontite, mesolite, natrolite, paragonite, phillipsite, prehnite, quartz, scapolites, scolecite, stilbite, thomsonite, zoisite.
Prehnite alters to	chlorite, quartz.
Pyrite alters to	hematite, limonite, magnetite.
Pyrope alters to	amesite, chlorite, enstatite, gibbsite, magnesite, quartz, serpentine, spinel, talc.
Pyrrhotite alters to	limonite magnetite, pyrite.
Rutile alters to	hematite, ilmenite, titanite.
Sahlite alters to	actinolite, bastite, calcite, chalcedony, magnetite, quartz, serpentine, talc.
Scapolite alters to	biotite, calcite, diaspore, epidote, gibbsite, hydromuscovite (pinite), kaolin, muscovite, quartz, talc.
Scolecite alters to	prehnite.
Serpentine alters to	brucite, hematite, limonite, magnesite, opal, quartz, webskyite.
Siderite alters to	grünerite, hematite, limonite, magnetite.
Sillimanite alters to	cyanite, kaolin, gibbsite, muscovite (damourite), talc.
Sodalite alters to	albite (conjectural), analcite, diaspore, gibbsite, hydromuscovite (pinite), hydronephelite, kaolin, muscovite, natrolite, nephelite (conjectural), thomsonite.
Spinel alters to	mica, serpentine, talc.
Spodumene alters to	albite, beta-spodumene, cymatolite, eucryphtite, microcline, muscovite.
Staurolite alters to	chlorite, gibbsite, magnetite, muscovite (damourite), talc.
Stilbite alters to	albite, orthoclase.
Titanite alters to	calcite, octahedrite, perovskite, quartz, rutile.
Topaz alters to	gibbsite, kaolin, muscovite, talc (steatite).
Tourmaline alters to	biotite, chlorite, gibbsite, mica, steatite.
Tremolite alters to	calcite, talc.
Vesuvianite alters to	chlorites, garnets, micas.
Zircon alters to	hydrous zircon (malacon).
Zoisite alters to	calcite, gibbsite, kaolin, quartz.

TABLE C.—*Chemical reactions and volume changes.*

Chemical reactions.	Source.	Products.	Volume change.
			Per cent.
(Not formulated)	Acmite	(Not recorded)	.....
$6CaMg_2FeSi_4O_{12}+4H_2O+6CO_2+3O=4H_2Mg_3Si_4O_{12}+6CaCO_3+3Fe_2O_3+8SiO_2$	Actinolite	Talc	−36.51
		Talc, calcite, hematite, quartz	+20.33
$Ca(MgFe)_3Si_4O_{12}+2H_2O+CO_2=H_4(MgFe)_3Si_2O_9+CaCO_3+2SiO_2$, or $Ca(Mg_2Fe)Si_4O_{12}+2H_2O+CO_2=H_4Mg_2FeSi_2O_9+CaCO_3+2SiO_2$	do	Bastite	−18.06
		Bastite, calcite, quartz	+38.67
$2NaAlSi_3O_8+2H_2O+CO_2=H_4Al_2Si_2O_9+4SiO_2+Na_2CO_3$	Albite	Kaolin, quartz	− 4.89
$2NaAlSi_3O_8+3H_2O+CO_2=2Al(OH)_3+6SiO_2+Na_2CO_3$	do	Gibbsite, quartz	+ 1.58
$6CaAl_2Si_2O_8+4NaAlSi_3O_8+6KAlSi_2O_6+48H_2O+2CO_2=3(K_2Ca_2Al_6Si_{12}O_{36}.14H_2O)+2Na_2CO_3+4Al(OH)_3$	Albite, anorthite, leucite	Phillipsite	+31.98
		Phillipsite, gibbsite	+40.61
$4NaAlSi_3O_8+3CaAl_2Si_2O_8+21H_2O+2CO_2=3(H_4CaAl_2Si_6O_{18}.3H_2O)+2Na_2CO_3+4Al(OH)_3$	Albite, anorthite	Heulandite, gibbsite	+37.14
$4NaAlSi_3O_8+3CaAl_2Si_2O_8+21H_2O+2CO_2=3(H_4CaAl_2Si_6O_{18}.3H_2O)+2Na_2CO_3+4Al(OH)_3$	do	Epistilbite, gibbsite	+37.14
$4NaAlSi_3O_8+3CaAl_2Si_2O_8+24H_2O+2CO_2=Ca_3Al_6(Si_3O_8)_6.18H_2O+2Na_2CO_3+4Al(OH)_3$	do	Stilbite, gibbsite	+43.50
$6NaAlSi_3O_8+6CaAl_2Si_2O_8+3CO_2+45H_2O=2[Ca_3Al_6(SiO_4)_3(Si_3O_8)_3.18H_2O]+3Na_2CO_3+6Al(OH)_3+6SiO_2$	do	Chabazite, gibbsite, quartz	+46.76
$2NaAlSi_3O_8+2H_2O=Na_2Al_2Si_4O_{12}.2H_2O+2SiO_2$	Albite	Analcite, quartz	+20.82
$2NaAlSi_3O_8+2H_2O=H_4Na_2Al_2Si_3O_{12}+3SiO_2$	do	Natrolite, quartz	+19.95
$4NaAlSi_3O_8+3CaAl_2Si_2O_8+13H_2O+CO_2=2(H_8Na_2CaAl_4Si_6O_{24}.H_2O)+6SiO_2+2Al(OH)_3+CaCO_3$	Albite, anorthite	Mesolite, gibbsite, quartz	+24.96
		Mesolite, gibbsite, quartz, calcite	+30.19
$3NaAlSi_3O_8+NaCl=Na_4Al_3Si_3O_{24}Cl$	Albite	Marialite	+10.29
	Albite, halite	do	+ 1.84
$NaAlSi_3O_8+2Al(OH)_3=NaH_2Al_3Si_3O_{12}+2H_2O$	Albite, gibbsite	Paragonite	−18.85
$x(NaAlSi_3O_8)+4(CaAl_2Si_2O_8)+KAlSi_3O_8+2H_2O=x(NaAlSi_3O_8)+2(HCa_2Al_3Si_3O_{13})+H_2KAl_3Si_3O_{12}+2SiO_2$	Albite, anorthite, orthoclase	Albite, zoisite, muscovite, quartz	.....
(Not formulated)	Allanite	(Not recorded)	.....
(Not formulated)	Almandite	Chlorite, Hypersthene, Spinel	One or more	.....

TABLE C.—*Chemical reactions and volume changes*—Continued.

Chemical reactions.	Source.	Products.	Volume change.
			Per cent.
$4Fe_3Al_2Si_3O_{12}.2Mg_3Al_2Si_3O_{12}+15H_2O=3H_{10}Fe_4Mg_2Al_4Si_4O_{25}+6SiO_2$	Almandite, pyrope	Aphrosiderite, quartz	+50.98
$Fe_3Al_2Si_3O_{12}.2Mg_3Al_2Si_3O_{12}=3MgFeSi_2O_6+3MgAl_2O_4+3SiO_2$	do	Hypersthene, spinel, quartz	+12.66
$3(2Mg_3Al_2Si_3O_{12}.Fe_3Al_2Si_3O_{12}.Ca_3Fe_2Si_3O_{12})+4CO_2=$ $5CaMg_2FeSi_4O_{12}.2[(Mg_4Fe_2)(Al_2Fe_2)Si_6O_{26}]+4CaCO_3+4SiO_2$	Almandite, pyrope, melanite	Hornblende, calcite, quartz	+24.55
$Na_2Al_2Si_4O_{12}.2H_2O+2SiO_2=2NaAlSi_3O_8+2H_2O$	Analcite, quartz	Albite	−17.25
$3(Na_2Al_2Si_4O_{12}.2H_2O)+4CaCO_3+K_2CO_3=2KAlSi_3O_8+2H_2Ca_2Al_2Si_3O_{12}+3Na_2CO_3+2CO_2+4H_2O$	Analcite	Orthoclase, prehnite	−14.09
$4Al_2SiO_5+3MgCO_3+13H_2O=H_2Mg_3Si_4O_{12}+8Al(OH)_3+3CO_2$	Andalusite	Talc (steatite)	−32.37
		Talc (steatite), gibbsite	+97.67
$2Al_2SiO_5+5H_2O=H_4Al_2Si_2O_9+2Al(OH)_3$	do	Kaolin	− 3.15
		Kaolin, gibbsite	+61.87
$6Al_2SiO_5+K_2CO_3+11H_2O=2H_2KAl_3Si_3O_{12}+6Al(OH)_3+CO_2$	do	Muscovite (damourite)	− 9.55
		Muscovite (damourite), gibbsite	+55.47
(Molecular change)	do	Cyanite	−12.03
$CaSO_4+2H_2O=CaSO_4.2H_2O$	Anhydrite	Gypsum	+60.30
$CaFeC_2O_6.CaMgC_2O_6+4SiO_2=MgFeCa_2Si_4O_{12}+4CO_2$	Ankerite, quartz	Sahlite	−37.27
$CaFe_3C_4O_{12}.CaMg_3C_4O_{12}+8SiO_2=Mg_3Fe_3Ca_2Si_8O_{24}+8CO_2$	do	Actinolite	−32.72
$3(CaFeC_2O_6.CaMgC_2O_6)+8SiO_2=Mg_3Fe_3Ca_2Si_8O_{24}+4CaCO_3+8CO_2$	do	Actinolite, calcite	−22.62
(Not formulated)	Ankerite and parankerite	Limonite, Hematite, Magnetite — One or more	....
$3CaAl_2Si_2O_8+7H_2O=Ca_3Al_6Si_6O_{24}.7H_2O$	Anorthite	Thomsonite	+34.65
$3CaAl_2Si_2O_8+12H_2O=Ca_3Al_6Si_6O_{25}.12H_2O$	do	Gismondite	+52.76
$2CaAl_2Si_2O_8+7H_2O+CO_2=H_4CaAl_2Si_4O_{14}.2H_2O+CaCO_3+2Al(OH)_3$	do	Laumontite, gibbsite	+33.65
$6CaAl_2Si_2O_8+4NaAlSi_3O_8+6KAlSi_2O_6+48H_2O+2CO_2=$ $3(K_2Ca_2Al_6Si_{12}O_{36}.14H_2O)+2Na_2CO_3+4Al(OH)_3$	Anorthite, albite, leucite	Phillipsite	+31.98
		Phillipsite, gibbsite	+40.61
$4NaAlSi_3O_8+3CaAl_2Si_2O_8+21H_2O+2CO_2=3(H_4CaAl_2Si_6O_{18}.3H_2O)+2Na_2CO_3+4Al(OH)_3$	Anorthite, albite	Heulandite, gibbsite	+37.14

TABLE C.—*Chemical reactions and volume changes*—Continued.

Chemical reactions.	Source.	Products.	Volume change.
			Per cent.
$4NaAlSi_3O_8+3CaAl_2Si_2O_8+21H_2O+2CO_2=3(H_4CaAl_2Si_6O_{18}.3H_2O)+2Na_2CO_3+4Al(OH)_3$	Anorthite, albite	Epistilbite, gibbsite	+37.14
$4NaAlSi_3O_8+3CaAl_2Si_2O_8+24H_2O+2CO_2=Ca_3Al_6(Si_2O_8)_3.18H_2O+2Na_2CO_3+4Al(OH)_3$	do	Stilbite, gibbsite	+43.50
$6NaAlSi_3O_8+6CaAl_2Si_2O_8+3CO_2+45H_2O=2[Ca_3Al_6(SiO_4)_3(Si_3O_8)_3.18H_2O]+3Na_2CO_3+6Al(OH)_3+6SiO_2$	do	Chabazite, gibbsite, quartz	+46.76
$3CaAl_2Si_2O_8+9H_2O+CO_2=2CaAl_2Si_3O_{10}.3H_2O+2Al(OH)_3+CaCO_3$	Anorthite	Scolecite, gibbsite	+35.23
$4NaAlSi_3O_8+3CaAl_2Si_2O_8+13H_2O+CO_2=2(H_8Na_2CaAl_4Si_6O_{24}.H_2O)+6SiO_2+2Al(OH)_3+CaCO_3$	Anorthite, albite	Mesolite, gibbsite, quartz	+24.96
		Mesolite, gibbsite, quartz, calcite	+30.19
$4CaAl_2Si_2O_8+8H_2O=2H_2Ca_2Al_2Si_3O_{12}+4Al(OH)_3+2SiO_2$	Anorthite	Prehnite, gibbsite, quartz	+14.85
$4CaAl_2Si_2O_8+3H_2O=H_2Ca_4Al_6Si_6O_{26}+H_4Al_2Si_2O_9$	do	Zoisite, kaolin	− 7.77
$4CaAl_2Si_2O_8+4H_2O=H_2Ca_4Al_6Si_6O_{26}+2Al(OH)_3+2SiO_2$	do	Zoisite, gibbsite, quartz	− 4.58
$4CaAl_2Si_2O_8+Fe_2O_3+6H_2O=H_2Ca_4Al_4Fe_2Si_6O_{26}+H_4Al_2Si_2O_9+2Al(OH)_3$	Anorthite, hematite	Epidote, kaolin, gibbsite	+ 3.60
$4CaAl_2Si_2O_8+7H_2O+Fe_2O_3=H_2Ca_4Al_4Fe_2Si_6O_{26}+4Al(OH)_3+2SiO_2$	do	Epidote, gibbsite, quartz	+ 6.57
$3CaAl_2Si_2O_8+CaCO_3=Ca_4Al_6Si_6O_{25}+CO_2$	Anorthite	Meionite	+ 7.87
	Anorthite, calcite	do	− 3.78
$x(NaAlSi_3O_8)+4(CaAl_2Si_2O_8)+KAlSi_3O_8+2H_2O=x(NaAlSi_3O_8)+2(HCa_2Al_3Si_3O_{13})+H_2KAl_3Si_3O_{12}+2SiO_2$	Anorthite, albite, orthoclase	Albite, zoisite, muscovite, quartz	.....
$2(2NaAlSi_3O_8.KAlSi_3O_8)+6H_2O+3CO_2=3H_4Al_2Si_2O_9+12SiO_2+K_2CO_3+2Na_2CO_3$	Anorthoclase	Kaolin, quartz	− 9.56
		Kaolin	−52.19
$2(2NaAlSi_3O_8.KAlSi_3O_8)+9H_2O+3CO_2=6Al(OH)_3+18SiO_2+K_2CO_3+2Na_2CO_3$	do	Gibbsite, quartz	− 3.30
		Gibbsite	−68.02
$2NaAlSi_3O_8.KAlSi_3O_8+6Al(OH)_3=KH_2Al_3Si_3O_{12}+2NaH_2Al_3Si_3O_{12}+6H_2O$	Anorthoclase, gibbsite	Muscovite, paragonite	−20.04
$2NaAlSi_3O_8.KAlSi_3O_8+MgCO_3+FeCO_3+5Al(OH)_3=11KMgFeAl_2Si_3O_{12}+2NaH_2Al_3Si_3O_{12}+5H_2O+2CO_2$	do	Biotite, paragonite	−10.91
$2(3NaAlSi_3O_8.KAlSi_3O_8)+2Fe_2O_3+8CaCO_3+2H_2O=4HCa_2Al_2FeSi_3O_{13}+12SiO_2+K_2CO_3+3Na_2CO_3+4CO_2$	Anorthoclase, hematite, calcite	Epidote, quartz	−28.30
$2Mg_3FeSi_4O_{12}+2H_2O+O=2H_2Mg_3Si_4O_{12}+Fe_2O_3$	Anthophyllite	Talc, hematite	+11.41
(Not formulated)	do	Talc, limonite	.....

TABLE C.—*Chemical reactions and volume changes*—Continued.

Chemical reactions.	Source.	Products.	Volume change.
			Per cent.
$3Mg_3FeSi_4O_{12}+8H_2O=H_{16}Mg_9Fe_3Si_8O_{36}+4SiO_2$	Anthophyllite	Bastite	+12.09
		Bastite, quartz	+34.09
(Substitution reaction)	do	Calcite	.....
(Not formulated)	Apatite	Osteolite	.....
$H_{14}Ca_4Si_6O_{23}+Na_2CO_3=2HNaCa_2Si_3O_9+6H_2O+CO_2$	Apophyllite	Pectolite	−19.48
(Molecular change)	Aragonite	Calcite	+ 8.35
(Not formulated)	Arfvedsonite	Acmite, Limenite, Magnetite, Lepidomelane (One or more)	....
$6[2(Ca_3Mg_2FeSi_6O_{18}).Mg_4Fe_2Al_9Fe_3Si_6O_{36}]+12CO_2+39H_2O+12O=$ $18(HCa_2Al_2FeSi_3O_{13})+3(H_{20}Mg_{12}Al_6Si_7O_{45})+33SiO_2+12Fe_2O_3+12MgCO_3$	Angite	Chlorite, epidote, quartz, hematite.	+ 8.58
	do	Chlorite, epidote, quartz, hematite, magnesite.	+15.43
$2[Ca_2MgFeSi_4O_{12}.(MgFe)(AlFe)_2SiO_6]+FeCO_3+MgCO_3=$ $Ca_2Mg_3Fe_3Si_8O_{24}.(MgFe)_2(AlFe)_4Si_2O_{12}+2CaCO_3$	Angite	Hornblende	+ 4.30
	Augite, siderite, magnesite	Hornblende, calcite	+ 6.14
$2[Ca_6Mg_4Fe_2Si_{12}O_{36}.Mg_4Fe_2Al_9Fe_3Si_6O_{36}]+6K_2CO_3+6H_2O+6CO_2=$ $2[H_6K_6Mg_8Fe_4Al_9Fe_3Si_{18}O_{72}]+12CaCO_3$	Augite	Biotite	+17.26
(Not formulated)	do	Serpentine, Magnetite (One or both)	....
(Not formulated)	Axinite	(Not recorded)	.....
$6KHMg_2Al_2Si_3O_{12}+18H_2O+3CO_2=4H_4Mg_3Si_2O_9+5H_4Al_2Si_2O_9+2Al(OH)_3+3K_2CO_3$	Biotite	Serpentine, kaolin, gibbsite	+14.26
$2HKMg_2Al_2Si_3O_{12}+7H_2O+CO_2=2(H_2Mg_2Al_2Si_3O_{12}.3H_2O)+K_2CO_3$	do	Hydrobiotite	+ 3.80
$2HKMg_2Al_2Si_3O_{12}+4MgCO_3+5H_2O=2[H_2Mg_4Al_2Si_3O_{12}.4(OH)]+K_2CO_3+3CO_2$	do	Chlorite	+22.92
$6H_2K_2Mg_3FeAl_4Si_6O_{24}+20CaCO_3+4CO_2+3O=$ $2H_6Ca_{10}Al_{12}Fe_3Si_{16}O_{65}+6SiO_2+18MgCO_3+6K_2CO_3+H_2O$	do	Epidote, quartz	−14.86

TABLE C.—*Chemical reactions and volume changes*—Continued.

Chemical reactions.	Source.	Products.	Volume change.
			Per cent.
$30KHMg_2Al_2Si_3O_{12}+6Fe_2O_3+40CaCO_3+35CO_2+H_2O=$ $4H_3Ca_{10}Al_{12}Fe_3Si_{15}O_{65}+30SiO_2+12AlO(OH)+60MgCO_3+15K_2CO_3$	Biotite, hematite	Epidote, quartz, diaspore	−18.45
$30KHMg_2Al_2Si_3O_{12}+6Fe_2O_3+40CaCO_3+29CO_2=$ $4H_3Ca_{10}Al_{12}Fe_3Si_{15}O_{65}+30SiO_2+6MgAl_2O_4+54MgCO_3+15K_2CO_3+5H_2O$	Biotite	Epidote, spinel, quartz	−14.71
	Biotite, hematite	do	−18.15
$60KHMg_2Al_2Si_3O_{12}+6Fe_2O_3+40CaCO_3+76H_2O=$ $30[H_2Mg_4Al_2Si_3O_{12}\cdot4(OH)]+4H_3Ca_{10}Al_{12}Fe_3Si_{15}O_{65}+30SiO_2+12AlO(OH)+30K_2CO_3+10CO_2$	do	Biotite-chlorite, epidote, quartz, diaspore.	+ 1.81
$H_2K_2Mg_3FeAl_4Si_6O_{24}+CO_2=Mg_3FeSi_4O_{12}+2Al_2SiO_5+H_2O+K_2CO_3$	Biotite	Hypersthene, sillimanite	−24.68
$3Mg_3FeSi_4O_{12}+3H_2O+O=3H_2Mg_3Si_4O_{12}+Fe_3O_4$	Bronzite or hypersthene	Talc, magnetite	[a] +14.68 [b] +21.73 [c] +18.20
(Not formulated)	do	Talc, hematite Talc, limonite One or both	....
$2Mg_3FeSi_4O_{12}+4H_2O+O=2H_4Mg_3Si_2O_9+Fe_2O_3+4SiO_2$	do	Serpentine, hematite	[b] − 2.21
		Serpentine, hematite, quartz	[b] +33.94
$3Mg_3FeSi_4O_{12}+8H_2O=H_{16}Mg_9Fe_3Si_8O_{36}+4SiO_2$	do	Bastite	[b] +22.77 [a] +15.65
		Bastite, quartz	[b] +46.87
(Molecular change)	do	Anthophyllite	[b] + 8.70
$3Mg_3FeSi_4O_{12}+4CaCO_3+4SiO_2=Mg_9Fe_3Ca_4Si_{16}O_{48}+4CO_2$	Bronzite or hypersthene, calcite, quartz.	Actinolite	[b] − 7.40 [a] −10.77
(Molecular change)	Brookite	Rutile	− 5.69
$4Mg(OH)_2+3CO_2=Mg_2(CO_3)_3.2Mg(OH).3H_2O$	Brucite	Hydromagnesite	+73.08
$H_6Na_6Ca(NaCO_3)_2Al_6Si_9O_{36}+6H_2O=3(Na_2Al_2Si_3O_{10}.2H_2O)+2Al(OH)_3+CaCO_3+Na_2CO_3$	Cancrinite	Natrolite, gibbsite, calcite	+ 8.64
$2CaCO_3+Mg=CaMg(CO_3)_2+Ca$	Calcite	Dolomite	−12.30
$2CaCO_3+MgCl_2=CaMgC_2O_6+CaCl_2$	do	do	−12.30

[a] Sp. gr. bronzite. [b] Sp. gr. hypersthene. [c] Av. sp. gr. hypersthene and bronzite.

TABLE C.—*Chemical reactions and volume changes*—Continued.

Chemical reactions.	Source.	Products.	Volume change.
			Per cent.
$2CaCO_3+MgCO_3=CaMgC_2O_6+CaCO_3$	Calcite	Dolomite	− 12.30
$CaCO_3+MgCO_3=CaMg(CO_3)_2$	do	do	+ 75.41
$CaCO_3+SiO_2=CaSiO_3+CO_2$	Calcite, quartz	Wollastonite	− 31.48
	Calcite	do	+ 10.81
$Ca_3Al_6Si_{12}O_{36}.18H_2O+2Al(OH)_3+4Na_2CO_3=4H_4Na_2Al_2Si_3O_{12}+3CaCO_3+CO_2+13H_2O$	Chabazite	Natrolite	− 4.58
(Recrystallization)	Chalcedony and chert	Quartz	.....
(Reactions variable)	do. (with bases)	Silicates	.....
(Not formulated)	Chlorites	Enophite, Berlanite, Quartz, Limonite — One or more	.....
(Not formulated)	Chlorites (with other minerals)	Micas, Feldspars, Ampbiboles, Pyroxenes, Olivines, Garnet, Clintonite, Staurolite, Tourmaline — Probable.	.....
(Not formulated)	Chloritoid	(Not recorded)	.....
$(MgF)_2Mg_3Si_2O_8+3H_2O=H_4Mg_3Si_2O_9+Mg(OH)_2+MgF_2$	Chondrodite	Serpentine, brucite	+ 30.15
(Not formulated)	Chromite	(Not recorded)	.....
$(MgF)_2Mg_7Si_4O_{16}+6H_2O=2H_4Mg_3Si_2O_9+2Mg(OH)_2+MgF_2$	Clinohumite	Serpentine, brucite	+ 38.39
$Al_2O_3+H_2O=2[AlO.(OH)]$	Corundum	Diaspore	+ 39.25
$Al_2O_3+3H_2O=2Al(OH)_3$	do	Gibbsite	+161.83

TABLE C.—*Chemical reactions and volume changes*—Continued.

Chemical reactions.	Source.	Products.	Volume change.
			Per cent.
$Al_2O_3+MgCO_3=MgAl_2O_4+CO_2$	Corundum, magnesite	Spinel	− 29.17
$Al_2O_3+SiO_2=Al_2SiO_5$	Corundum, quartz	Sillimanite	+ 4.38
$Al_2O_3+SiO_2=Al_2SiO_5$	do	Cyanite	− 6.59
$3Al_2O_3+6SiO_2+K_2CO_3+2H_2O=2H_2KAl_3Si_3O_{12}+CO_2$	Corundum	Muscovite (damourite)	+264.25
	Corundum, quartz, K_2CO_3	do	+ 1.62
$2Al_2O_3+2SiO_2+CaCO_3+H_2O=H_2CaAl_4Si_2O_{12}+CO_2$	Corundum	Margarite	+159.02
	Corundum, quartz, calcite	do	− 1.22
$3Al_2O_3+6SiO_2+4CaCO_3+H_2O=H_2Ca_4Al_6Si_6O_{26}+4CO_2$	Corundum	Zoisite	+261.34
	Corundum, quartz, calcite	do	− 23.58
$3(MgFe)SiO_3+2H_2O=H_4(MgFe)_3Si_2O_9+SiO_2$, or	Cummingtonite	Bastite	+ 14.20
$3(Mg_3FeSi_4O_{12})+8H_2O=H_{16}Mg_9Fe_3Si_8O_{36}+4SiO_2$	do	Bastite, quartz	+ 36.76
$4Al_2SiO_5+3MgCO_3+13H_2O=H_2Mg_3Si_4O_{12}+8Al(OH)_3+3CO_2$	Cyanite	Talc (steatite)	− 23.12
		Talc (steatite), gibbsite	+124.71
$2Al_2SiO_5+5H_2O=H_4Al_2Si_2O_9+2Al(OH)_3$	do	Kaolin	+ 10.11
		Kaolin, gibbsite	+ 84.02
$6Al_2SiO_5+K_2CO_3+11H_2O=2H_2KAl_3Si_3O_{12}+6Al(OH)_3+CO_2$	do	Muscovite (damourite)	+ 2.83
		Muscovite (damourite), gibbsite	+ 76.74
(Not formulated)	Diallage	Chlorite, Epidote, Magnetite, Calcite, Feldspar, Smaragdite, Quartz — One or more	.....
$2AlO(OH)=Al_2O_3+H_2O$	Diaspore	Corundum	− 28.18
$2AlO(OH)+MgCO_3=MgAl_2O_4+CO_2+H_2O$	Diaspore, magnesite	Spinel	− 40.39
$2AlO(OH)+SiO_2=Al_2SiO_5+H_2O$	Diaspore, quartz	Sillimanite	− 13.52

TABLE C.—*Chemical reactions and volume changes*—Continued.

Chemical reactions.	Source.	Products.	Volume change.
			Per cent.
$2AlO(OH)+SiO_2=Al_2SiO_5+H_2O$	Diaspore, quartz	Cyanite	−22.61
$6AlO(OH)+6SiO_2+K_2CO_3=2H_2KAl_3Si_3O_{12}+CO_2+H_2O$	Diaspore, quartz, K_2CO_3	Muscovite	−54.21
$4AlO(OH)+2SiO_2+CaCO_3=H_2CaAl_4Si_2O_{12}+CO_2+H_2O$	Diaspore, quartz, calcite	Margarite	−14.08
$6AlO(OH)+6SiO_2+4CaCO_3=H_2Ca_4Al_6Si_6O_{26}+4CO_2+2H_2O$	do	Zoisite	−29.44
$3CaMgSi_2O_6+3CO_2+H_2O=H_2Mg_3Si_4O_{12}+3CaCO_3+2SiO_2$	Diopside	Talc	−30.13
		Talc, calcite, quartz	+48.74
$3CaMgSi_2O_6+3CO_2+2H_2O=H_4Mg_3Si_2O_9+4SiO_2+3CaCO_3$	do	Serpentine, quartz	+ 0.44
		Serpentine, quartz, calcite	+56.32
$2CaMgSi_2O_6+MgCO_3=CaMg_3Si_4O_{12}+CaCO_3$	do	Tremolite	+ 5.68
	Diopside, magnesite	Tremolite, calcite	+10.55
(Not formulated)	Diopside	Epidote, Chlorite — One or both	.....
$MgCaC_2O_6+2SiO_2=MgCaSi_2O_6+2CO_2$	Dolomite	Diopside	+ 2.03
	Dolomite, quartz	do	−40.11
$3MgCaC_2O_6+4SiO_2=Mg_3CaSi_4O_{12}+2CaCO_3+4CO_2$	Dolomite	Tremolite, calcite	+ 9.89
	Dolomite, quartz	do	−25.20
$3MgCaC_2O_6+6SiO_2=Mg_3CaSi_4O_{12}+2CaSiO_3+6CO_2$	Dolomite	Tremolite, wollastonite	+14.00
	Dolomite, quartz	do	−33.09
$4MgSiO_3+CO_2+H_2O=H_2Mg_3Si_4O_{12}+MgCO_3$	Enstatite	Talc	+ 9.93
$3MgSiO_3+2H_2O=H_4Mg_3Si_2O_9+SiO_2$	do	Serpentine	+14.25
		Serpentine, quartz	+38.36
(Not formulated)	do	Bastite, Actinolite, Anthophyllite — One or more	.....
$Ca_6(AlOH)_3Al_4Fe_2Si_9O_{36}+6CO_2+8\frac{1}{2}H_2O=6CaCO_3+3Al(OH)_3+2H_4Al_2Si_2O_9+Fe_2O_3.1\frac{1}{2}H_2O+5SiO_2$	Epidote	Calcite, gibbsite, kaolin, limonite, quartz	+69.08

TABLE C.—*Chemical reactions and volume changes*—Continued.

Chemical reactions.	Source.	Products.	Volume change.
			Per cent.
(Not formulated)	Epidote	Probable: Mica	
		Probable: Amphibole	
		Probable: Pyroxene, etc.	
(Not formulated)	Fayalite	(Not recorded)	
$CaF_2+Na_2CO_3=CaCO_3+2NaF$	Fluorite	Calcite	+47.66
$3Mg_2SiO_4+2CaCO_3+5SiO_2=2Mg_3CaSi_4O_{12}+2CO_2$	Forsterite, calcite, quartz	Tremolite	−12.29
$4Fe_3Al_2Si_3O_{12}.2Mg_3Al_2Si_3O_{12}+15H_2O=3H_{10}Fe_4Mg_2Al_4Si_4O_{25}+6SiO_2$	Garnet (almandite and pyrope)	Aphrosiderite, quartz	+50.98
$Fe_3Al_2Si_3O_{12}.2Mg_3Al_2Si_3O_{12}=3MgFeSi_2O_6+3MgAl_2O_4+3SiO_2$	do	Hypersthene, spinel, quartz	+12.66
$2Ca_3Al_2Si_3O_{12}.Ca_3Fe_2Si_3O_{12}+5CO_2+H_2O=2HCa_2Al_2FeSi_3O_{13}+5CaCO_3+3SiO_2$	Garnet (grossularite and melanite).	Epidote, calcite, quartz	+40.88
$Ca_3Al_2Si_3O_{12}.Mg_3Al_2Si_3O_{12}.Ca_3Fe_2Si_3O_{12}+H_2O+5CO_2=2HCa_2Al_2FeSi_3O_{13}+2CaCO_3+3MgCO_3+3SiO_2$	Garnet (grossularite, pyrope, melanite).	Epidote, calcite, magnesite, quartz.	+39.53
$3(2Mg_3Al_2Si_3O_{12}.Fe_3Al_2Si_3O_{12}.Ca_3Fe_2Si_3O_{12})+4CO_2=5CaMg_2FeSi_4O_{12}.2[(Mg_4Fe_2)(Al_2Fe_3)Si_6O_{26}]+4CaCO_3+4SiO_2$	Garnet (pyrope, almandite, melanite).	Hornblende, calcite, quartz	+24.55
(Not formulated)	Gedrite	(Not recorded)	
$Ca_3Al_2Si_2O_{10}+SiO_2=Ca_3Al_2Si_3O_{12}$	Gehlenite	Grossularite	− 4.42
	Geblenite, quartz	do	−18.56
(Not formulated)	Gehlenite	Talc, Fassalite: One or both	
$Al(OH)_3=AlO(OH)+H_2O$	Gibbsite	Diaspore	−46.82
$2Al(OH)_3=Al_2O_3+3H_2O$	do	Corundum	−61.81
$2Al(OH)_3+MgCO_3=MgAl_2O_4+CO_2+3H_2O$	Gibbsite, magnesite	Spinel	−60.12
$2Al(OH)_3+SiO_2=Al_2SiO_5+3H_2O$	Gibbsite, quartz	Sillimanite	−43.68
$2Al(OH)_3+SiO_2=Al_2SiO_5+3H_2O$	do	Cyanite	−49.61
$6Al(OH)_3+6SiO_2+K_2CO_3=2H_2KAl_3Si_3O_{12}+CO_2+7H_2O$	Gibbsite, quartz, K_2CO_3	Muscovite	−64.99
$4Al(OH)_3+2SiO_2+CaCO_3=H_2CaAl_4Si_2O_{12}+CO_2+5H_2O$	Gibbsite, quartz, calcite	Margarite	−38.92
$6Al(OH)_3+6SiO_2+4CaCO_3=H_2Ca_4Al_6Si_6O_{26}+4CO_2+8H_2O$	do	Zoisite	−43.06

TABLE C.—*Chemical reactions and volume changes*—Continued.

Chemical reactions.	Source.	Products.	Volume change.
			Per cent.
(Not formulated)	Glass	(Variable)	.....
	Glauconite	(Not recorded)	.....
	Glaucophane	(Not recorded)	.....
	Graphite	(Not recorded)	.....
$3Ca_3Al_2Si_3O_{12}+5CO_2=Ca_4Al_6Si_6O_{25}+5CaCO_3+3SiO_2$	Grossularite	Meionite, calcite, quartz	+54.62
$3Ca_3Al_2Si_3O_{12}+5CO_2+H_2O=2HCa_2Al_3Si_3O_{13}+5CaCO_3+3SiO_2$	do	Zoisite, calcite, quartz	+40.49
$2Ca_3Al_2Si_3O_{12}.Ca_3Fe_2Si_3O_{12}+5CO_2+H_2O=2HCa_2Al_2FeSi_3O_{13}+5CaCO_3+3SiO_2$	Grossularite, melanite	Epidote, calcite, quartz	+40.88
$Ca_3Al_2Si_3O_{12}.Mg_3Al_2Si_3O_{12}.Ca_3Fe_2Si_3O_{12}+H_2O+5CO_2=2HCa_2Al_2FeSi_3O_{13}+2CaCO_3+3MgCO_3+3SiO_2$	Grossularite, pyrope, melanite	Epidote, calcite, magnesite, quartz	+39.53
(Not formulated)	Grünerite	Hematite / Limonite / Magnetite — One or more	..... / ..... / .....
$CaSO_4.2H_2O=CaSO_4+2H_2O$	Gypsum	Anhydrite	−37.62
$CaSO_4.2H_2O+CO_2=CaCO_3+H_2SO_4+H_2O$	do	Calcite	−50.29
$2Na_2Ca(NaSO_4.Al)Al_2Si_3O_{12}+2CO_2+8H_2O=2(H_4Na_2Al_2Si_3O_{12})+2Al(OH)_3+2CaCO_3+2NaHSO_4$	Haüynite	Natrolite, gibbsite, calcite	+ 4.99
$6Na_2Ca(NaSO_4.Al)Al_2Si_3O_{12}+36H_2O+6CO_2=Ca_3Al_6(Si_3O_8)_6.18H_2O+12Al(OH)_3+3CaCO_3+6Na_2SO_4+3Na_2CO_3$	do	Stilbite, gibbsite, calcite	+ 0.46
$4Na_2Ca(NaSO_4.Al)Al_2Si_3O_{12}+24H_2O+6CO_2=Ca_3Al_6(SiO_4)_3(Si_3O_8)_3.18H_2O+4Al(OH)_3+CaSO_4+Al_2(SO_4)_3+6Na_2CO_3$	do	Chabazite, gibbsite	− 7.46
(Not formulated)	Hedenbergite	(Not recorded)	.....
$2Fe_2O_3+3H_2O=2Fe_2O_3.3H_2O$	Hematite	Limonite	+60.72
$3Fe_2O_3+CO=2Fe_3O_4+CO_2$	do	Magnetite	− 2.38
$Fe_2O_3+2H_2S+CO_2=FeS_2+FeCO_3+2H_2O$	do	Pyrite, siderite	+76.12
$Fe_2O_3+2H_2S+CO_2=FeS_2+FeCO_3+2H_2O$	do	Marcasite, siderite	+78.73
$H_4CaAl_2Si_6O_{18}.3H_2O+Na_2CO_3=2NaAlSi_3O_8+CaCO_3+5H_2O$	Heulandite	Albite	−25.03
$H_4CaAl_2Si_6O_{18}.3H_2O+K_2CO_3=2KAlSi_3O_8+CaCO_3+5H_2O$	do	Orthoclase	−18.44
$8CaMg_2FeSi_4O_{12}.2Mg_4Fe_2Al_8Fe_4Si_6O_{36}+21H_2O+16CO_2=2(H_{30}Mg_{12}Al_6Si_7O_{45})+2HCa_2Al_2FeSi_3O_{13}+4CaCO_3+12FeCO_3+24SiO_2+3Fe_2O_3$	Hornblende	Chlorite, epidote, calcite, siderite, quartz, hematite.	+25.39

TABLE C.—*Chemical reactions and volume changes*—Continued.

Chemical reactions.	Source.	Products.	Volume change.
			Per cent.
$2Ca(MgFe)_3Si_4O_{12}.3(MgFe)_2(AlFe)_4Si_2O_{12}+3K_2SiO_3+SiO_2+3H_2O+2CO_2=$ $6HK(MgFe)_2(AlFe)_2Si_2O_{12}+2CaCO_3$, or $2(CaMg_2FeSi_4O_{12}).Mg_4Fe_2Al_8Fe_4Si_6O_{36}+3K_2SiO_3+SiO_2+3H_2O+2CO_2=$ $H_6K_6Mg_8Fe_4Al_8Fe_4Si_{13}O_{72}+2CaCO_3$.	Hornblende, quartz	Biotite, calcite	+41.13
$8Ca(MgFe)_3Si_4O_{12}.18(MgFe)_2(AlFe)_4Si_2O_{12}+15K_2SiO_3+19SiO_2+17H_2O=$ $30HK(MgFe)_2(AlFe)_2Si_2O_{12}+4HCa_2(AlFe)_8Si_3O_{13}$, or $8CaMg_2FeSi_4O_{12}.6Mg_4Fe_2Al_8Fe_4Si_6O_{36}+15K_2SiO_3+19SiO_2+17H_2O=$ $10H_6K_2Mg_4Fe_2Al_4Fe_2Si_2O_{36}+H_4Ca_8Al_8Fe_4Si_{12}O_{52}$.	do	Biotite, epidote	+30.05
$Ca_2Mg_3Fe_3Si_8O_{24}.(MgFe)_2(AlFe)_4Si_2O_{12}+2CaCO_3=$ $2[Ca_2MgFeSi_4O_{12}.(MgFe)(AlFe)_2SiO_5]+FeCO_3+MgCO_3$, or $Ca_2Mg_3Fe_3Si_8O_{24}.Mg_4Fe_2Al_8Fe_4Si_6O_{36}+2CaCO_3=$ $2[Ca_2MgFeSi_4O_{12}.Mg_2FeAl_4Fe_2Si_3O_{18}]+FeCO_3+MgCO_3$.	Hornblende	Augite	−4.13
(Not formulated)	do	Serpentine, Magnetite — With other products	....
$2(MgF)_2Mg_5Si_3O_{12}+9H_2O=3H_4Mg_3Si_2O_9+3Mg(OH)_2+2MgF_2$	Humite	Serpentine, brucite	+35.53
$3MgFeSi_2O_6+H_2O+O=H_2Mg_3Si_4O_{12}+Fe_3O_4+2SiO_2$	Hypersthene	Tale, magnetite, quartz	+12.84
$3MgFeSi_2O_6+2H_2O+O=H_4Mg_3Si_2O_9+Fe_3O_4+4SiO_2$	do	Serpentine, magnetite, quartz	+20.24
(*See* Bronzite)	do	(*See* Bronzite.)	
$3FeTiO_3+3CaCO_3+3SiO_2+O=3CaTiSiO_5+Fe_3O_4+3CO_2$	Ilmenite	Titanite	+76.35
	Ilmenite, calcite, quartz	Titanite, magnetite	−22.35
(Not formulated)	Ilmenite	Titanite, hematite / Titanite, limonite — One or both	....
$3FeTiO_3+O=3TiO_2+Fe_3O_4$	do	Rutile, magnetite	+6.02
$2FeTiO_3+O=2TiO_2+Fe_2O_3$	do	Rutile, hematite	+7.16
(Not formulated)	do	Rutile, limonite	.....
$3FeTiO_3+O=3TiO_2+Fe_3O_4$	do	Octahedrite, magnetite	+11.07
$2FeTiO_3+O=2TiO_2+Fe_2O_3$	do	Octahedrite, hematite	+12.20

TABLE C.—*Chemical reactions and volume changes*—Continued.

Chemical reactions.	Source.	Products.	Volume change.
			Per cent.
(Not formulated)	Ilmenite	Octahedrite, limonite	.....
$H_2(MgFe)_4Al_8Si_{10}O_{37}+3H_2O=H_8(MgFe)_4Al_8Si_{10}O_{40}$, or $H_2Mg_3FeAl_8Si_{10}O_{37}+3H_2O=H_8Mg_3FeAl_8Si_{10}O_{40}$.	Iolite (cordierite)	Chlorophyllite	− 0.86
(Not formulated)	....do	Pinite... / Chlorite. } One or both	..... / .....
(Not formulated)	Kaolin	(Not recorded)	.....
$Ca_3Al_6Si_{12}O_{36}.12H_2O+2Na_2CO_3+CO_2=4NaAlSi_3O_8+Al_2O_3+3CaCO_3+12H_2O$	Laumontite	Albite	− 34.92
$Ca_3Al_6Si_{12}O_{36}.12H_2O+CaCO_3+K_2CO_3=2KAlSi_3O_8+2H_2Ca_2Al_2Si_3O_{12}+2CO_2+10H_2O$	....do	Orthoclase, prehnite	− 17.75
$Ca_3Al_6Si_{12}O_{36}.12H_2O+3Na_2CO_3=3(Na_2Al_2Si_4O_{12}.2H_2O)+3CaCO_3+6H_2O$	....do	Analcite	− 4.30
$6KAlSi_2O_6+6CaAl_2Si_2O_8+4NaAlSi_3O_8+48H_2O+2CO_2=3(K_2Ca_2Al_6Si_{12}O_{36}.14H_2O)+2Na_2CO_3+4Al(OH)_3$	Leucite, anortbite, albite	Phillipsite / Phillipsite, gibbsite	+ 31.98 / + 40.61
$2KAlSi_2O_6+Na_2CO_3+2H_2O=Na_2Al_2Si_4O_{12}.2H_2O+K_2CO_3$	Leucite	Analcite	+ 10.74
$4KAlSi_2O_6+CO_2+2H_2O=2KAlSi_3O_8+H_4Al_2Si_2O_9+K_2CO_3$	....do	Orthoclase / Orthoclase, kaolin	− 38.57 / − 10.58
$6KAlSi_2O_6+CO_2+H_2O=3KAlSi_3O_8+KH_2Al_3Si_3O_{12}+K_2CO_3$	....do	Orthoclase, muscovite	− 12.43
$4KAlSi_2O_6+Na_2CO_3=2KAlSi_3O_8+2NaAlSiO_4+K_2CO_3$	....do	Orthoclase, nephelite	− 7.59
$2Fe_2O_3.3H_2O=2Fe_2O_3+3H_2O$	Limonite	Hematite	− 37.78
$2Fe_2O_3.3H_2O+2CO+2CO_2=4FeCO_3+3H_2O$	....do	Siderite	+ 22.27
$2Fe_2O_3.3H_2O+C+3CO_2=4FeCO_3+3H_2O$	....do	....do	+ 22.27
$2Fe_2O_3.3H_2O+2C+4CO_2=4FeCO_3+3H_2O+2CO$	....do	....do	+ 22.27
(Not formulated)	Magnesite	Enstatite / Tremolite / Olivine / Pyrope, etc } Probable.	..... / ..... / ..... / .....
$2Fe_3O_4+O=3Fe_2O_3$	Magnetite	Hematite	+ 2.44
$4Fe_3O_4+2O+9H_2O=3(2Fe_2O_3.3H_2O)$	....do	Limonite	+ 64.63
$Fe_3O_4+CO+2CO_2=3FeCO_3$	....do	Siderite	+101.30

TABLE C.—*Chemical reactions and volume changes*—Continued.

Chemical reactions.	Source.	Products.	Volume change.
			Per cent.
$4FeS_2+22O+3H_2O=2Fe_2O_3.3H_2O+8SO_2$	Marcasite	Limonite	+ 0.14
$FeS_2+6O=FeSO_4+SO_3$ or $FeS_2+3O+H_2O=FeSO_4+H_2S$ $4FeSO_4+2O+7H_2O=2Fe_2O_3.3H_2O+4H_2SO_4$	do	do	
$3FeS_2+16O=Fe_3O_4+6SO_2$	do	Magnetite	−39.34
$3FeS_2+4H_2O+4O=Fe_3O_4+4H_2S+2SO_2$	do	do	−39.34
(Molecular change)	do	Pyrite	− 2.98
(Not formulated)	do	Hematite	
(Not formulated)	Margarite	Dudleyite	
$2Na_4Al_3Si_3O_{24}Cl+9MgCO_3+9H_2O=3H_4Al_2Si_2O_9+3H_2Mg_3Si_4O_{12}+3Na_2CO_3+2NaCl+6CO_2$	Marialite	Kaolin, talc	+ 7.69
$2Na_4Al_3Si_3O_{24}Cl+K_2CO_3+2H_2O+2CO_2=2KH_2Al_3Si_3O_{12}+12SiO_2+2NaCl+3Na_2CO_3$	do	Muscovite, quartz	−16.74
(Not formulated)	do	Biotite	
$Ca_4Al_6Si_6O_{25}+6H_2O+4CO_2=3H_4Al_2Si_2O_9+4CaCO_3$	Meionite	Kaolin, calcite	+35.40
$Ca_4Al_6Si_6O_{25}+K_2CO_3+3CO_2+2H_2O=2KH_2Al_3Si_3O_{12}+4CaCO_3$	do	Muscovite, calcite	+29.42
$Ca_4Al_6Si_6O_{25}+Fe_2O_3+4H_2O=2HCa_2Al_2FeSi_3O_{13}+2Al(OH)_3$	Meionite, hematite	Epidote, gibbsite	− 1.62
$Ca_4Al_6Si_6O_{25}+2FeCO_3+4H_2O+O=2HCa_2Al_2FeSi_3O_{13}+2Al(OH)_3+2CO_2$	Meionite	do	+ 7.55
(Not formulated)	do	Biotite	
$2Ca_3Al_2Si_3O_{12}.Ca_3Fe_2Si_3O_{12}+5CO_2+H_2O=2HCa_2Al_2FeSi_3O_{13}+5CaCO_3+3SiO_2$	Melanite, grossularite	Epidote, calcite, quartz	+40.88
$Ca_3Al_2Si_3O_{12}.Mg_3Al_2Si_3O_{12}.Ca_3Fe_2Si_3O_{12}+H_2O+5CO_2=2HCa_2Al_2FeSi_3O_{13}+2CaCO_3+3MgCO_3+3SiO_2$	Melanite, pyrope, grossularite	Epidote, calcite, magnesite, quartz	+39.53
$3(2Mg_3Al_2Si_3O_{12}.Fe_3Al_2Si_3O_{12}.Ca_3Fe_2Si_3O_{12})+4CO_2=$ $5CaMg_2FeSi_4O_{12}.2(Mg_4Fe_2)(Al_2Fe_3)Si_6O_{36}+4CaCO_3+4SiO_2$	Melanite, pyrope, almandite	Hornblende, calcite, quartz	+24.55
(Not formulated)	Melilite	(Not recorded)	
$H_2Na_2CaAl_4Si_6O_{21}.4H_2O+3CaCO_3=2H_2Ca_2Al_2Si_3O_{12}+Na_2CO_3+2CO_2+3H_2O$	Mesolite	Prehnite	−15.05
	Microcline (*see* Orthoclase).		
$2KH_2Al_3Si_3O_{12}+9MgCO_3+13H_2O=3H_4Mg_3Si_2O_9+6Al(OH)_3+K_2CO_3+8CO_2$	Muscovite	Serpentine	+16.56
		Serpentine, gibbsite	+88.44
$4KH_2Al_3Si_3O_{12}+9MgCO_3+17H_2O=3H_2Mg_3Si_4O_{12}+12Al(OH)_3+2K_2CO_3+7CO_2$	do	Talc	−25.23
		Talc, gibbsite	+46.69

TABLE C.—*Chemical reactions and volume changes*—Continued.

Chemical reactions.	Source.	Products.	Volume change.
			Per cent.
$2H_2KAl_3Si_3O_{12}+Na_2CO_3=2H_2NaAl_3Si_3O_{12}+K_2CO_3$	Muscovite	Paragonite	− 2.67
(Not formulated)	do	Vermiculite	.....
$Na_2Al_2Si_3O_{10}.2H_2O+2CaCO_3=H_2Ca_2Al_2Si_3O_{12}+Na_2CO_3+CO_2+H_2O$	Natrolite	Prehnite	−16.12
$6NaAlSiO_4+7H_2O+CO_2=2HNa_2Al_3Si_3O_{12}.3H_2O+Na_2CO_3$	Nephelite	Hydronephelite	+23.49
$6NaAlSiO_4+7H_2O+CO_2=2Na_2Al_2H_4Si_3O_{12}+2Al(OH)_3+Na_2CO_3$	do	Natrolite, gibbsite	+24.46
$6NaAlSiO_4+5H_2O+CO_2=2Na_2Al_2H_4Si_3O_{12}+2AlO(OH)+Na_2CO_3$	do	Natrolite, diaspore	+15.00
$6NaAlSiO_4+7H_2O+3CaCO_3=Ca_3Al_6Si_6O_{24}.7H_2O+3Na_2CO_3$	do	Thomsonite	+24.60
$4NaAlSiO_4+3H_2O+CO_2=Na_2Al_2Si_4O_{12}.2H_2O+2AlO(OH)+Na_2CO_3$	do	Analcite, diaspore	+ 5.49
$4NaAlSiO_4+5H_2O+CO_2=Na_2Al_2Si_4O_{12}.2H_2O+2Al(OH)_3+Na_2CO_3$	do	Analcite, gibbsite	+19.68
$2KNa_3Al_4Si_4O_{16}+4H_2O+3CO_2=2KH_2Al_3Si_3O_{12}+H_4Al_2Si_2O_9+3Na_2CO_3$	do	Muscovite Muscovite, kaolin	−38.46 −16.50
(Not formulated)	do	Pinite, kaolin	−13.00
$3NaAlSiO_4+NaCl=NaCl.3NaAlSiO_4$	do Nephelite, halite	Sodalite do	+33.14 +15.64
$NaAlSiO_4+2SiO_2=NaAlSi_3O_8$	Nephelite, quartz	Albite	− 0.41
$2Na_4(NaSO_4.Al)Al_2Si_3O_{12}+CO_2+7H_2O=2H_4Na_2Al_2Si_3O_{12}+2Al(OH)_3+2Na_2SO_4+Na_2CO_3$	Noselite	Natrolite, gibbsite	−16.44
(Molecular change)	Octahedrite (anatase)	Rutile	− 7.83
	Oligoclase (*see* Andesine.)		
$3Mg_3FeSi_2O_8+6H_2O+O=3H_4Mg_3Si_2O_9+Fe_3O_4$	Olivine	Serpentine, magnetite	+29.96
$3Mg_3FeSi_2O_8+3CO_2+4H_2O+O=2H_4Mg_3Si_2O_9+Fe_3O_4+3MgCO_3+2SiO_2$	do	Serpentine, magnetite, magnesite, quartz.	+37.13
$3Mg_2Fe_2Si_2O_8+4H_2O+2O=2H_4Mg_3Si_2O_9+2Fe_3O_4+2SiO_2$	do	Serpentine, magnetite, quartz	+12.43
$3MgFeSiO_4+2H_2O+O=H_4Mg_3Si_2O_9+Fe_3O_4+SiO_2$	do	do	+15.19
$Mg_3FeSi_2O_8+2SiO_2=Mg_3FeSi_4O_{12}$	Olivine, quartz	Anthophyllite	− 1.48
$3Mg_3FeSi_2O_8+4CaCO_3+10SiO_2=Mg_9Fe_3Ca_4Si_{16}O_{48}+4CO_2$	Olivine, calcite, quartz	Actinolite	−13.34
$4Mg_3FeSi_2O_8+4CaAl_2Si_2O_8=Mg_9Fe_3Ca_4Si_{16}O_{48}+3MgAl_2O_4+FeAl_2O_4$	Olivine, anorthite	Actinolite, spinel	− 7.18
$SiO_2.\frac{1}{3}H_2O=SiO_2+\frac{1}{3}H_2O$	Opal	Quartz	−22.81

TABLE C.—*Chemical reactions and volume changes*—Continued.

Chemical reactions.	Source.	Products.	Volume change.
			Per cent.
(Not formulated)	Opal	Chert	
		Chalcedony	
(Not formulated)	Opal (with bases)	Silicates	
$2KAlSi_3O_8+2H_2O+CO_2=H_4Al_2Si_2O_9+4SiO_2+K_2CO_3$	Orthoclase or microcline	Kaolin	−54.44
		Kaolin, quartz	−12.57
(Similar reactions except in amount H_2O added, and of SiO_2 which separates)	do	Halloysite, Newtonite, Cimolite, Pyrophyllite, Allophane — One or more	
$2KAlSi_3O_8+3H_2O+CO_2=2Al(OH)_3+6SiO_3+K_2CO_3$	Orthoclase or microcline	Gibbsite, quartz	− 6.61
$3KAlSi_3O_8+1H_2O+CO_2=KH_2Al_3Si_3O_{12}+6SiO_2+K_2CO_3$	do	Muscovite, quartz	−15.58
$KAlSi_3O_8+2Al(OH)_3=KH_2Al_3Si_3O_{12}+2H_2O$	Orthoclase or microcline, gibbsite	Muscovite (damourite)	−20.81
$4KAlSi_3O_8+2MgCO_3+2FeCO_3+H_2O=2HKMgFeAl_2Si_3O_{12}+5SiO_2+K_2SiO_3+4CO_2$	Orthoclase or microcline, magnesite, siderite.	Biotite, quartz	−22.64
$KAlSi_3O_8+MgCO_3+FeCO_3+Al(OH)_3=HKMgFeAl_2Si_3O_{12}+H_2O+2CO_2$	Orthoclase or microcline, magnesite, siderite, gibbsite.	Biotite	−22.33
$4KAlSi_3O_8+Fe_2O_3+4CaCO_3+H_2O=2HCa_2Al_2FeSi_3O_{13}+6SiO_2+2K_2CO_3+2CO_2$	Orthoclase or microcline, calcite, hematite.	Epidote, quartz	-33.73
$x(NaAlSi_3O_8)+4(CaAl_2Si_2O_8)+KAlSi_3O_8+2H_2O=x(NaAlSi_3O_8)+2(HCa_2Al_3Si_3O_{13})+H_2KAl_3Si_3O_{12}+2SiO_2$	Orthoclase, albite, anorthite	Albite, zoisite, muscovite, quartz.	
(Not formulated)	Ottrelite	(Not recorded)	
(Not formulated)	Paragonite	Probably analogous to muscovite.	
	Parankerite (*see* Ankerite).		
(Not formulated)	Pectolite	(Not recorded)	
(Not formulated)	Perovskite	Ilmenite	
$2H_2KMg_3AlSi_3O_{12}+7H_2O+CO_2=2(H_8Mg_3AlSi_3O_{12}.3H_2O)+K_2CO_3$	Phlogopite	Hydrophlogopite	+26.89
$2H_2KMg_3AlSi_3O_{12}+6MgCO_3+7H_2O=2[H_8Mg_6AlSi_3O_{12}6(OH)]+K_2CO_3+5CO_2$	do	Chlorite	+41.02

TABLE C.—*Chemical reactions and volume changes*—Continued.

Chemical reactions.	Source.	Products.	Volume change.
			Per cent.
$4H_2KMg_3AlSi_3O_{12}+6H_2O+4CO_2=3H_2Mg_3Si_4O_{12}+4Al(OH)_3+3MgCO_3+K_2CO_3+H_2O$	Phlogopite	Talc, gibbsite	− 7.79
$4H_2KMg_3AlSi_3O_{12}+2H_2O+4CO=3H_2Mg_3Si_4O_{12}+4AlO(OH)+3MgCO_3+K_2CO_3+H_2O$	do	Talc, diaspore	−18.27
$2H_2KMg_3AlSi_3O_{12}+CO_2+4H_2O=H_2Mg_3Si_4O_{12}+H_4Mg_3Si_2O_9+2Al(OH)_3+K_2CO_3$	do	Talc, serpentine, gibbsite	+ 5.23
(Not formulated)	do	Penninite, Clinochlore } One or both	....
(Not formulated)	Piedmontite	(Not recorded)	.....
$H_2Ca_2Al_2Si_3O_{12}+2MgCO_3+H_2O=H_4Mg_2Al_2SiO_9+2SiO_2+2CaCO_3$	Prehnite	Chlorite, quartz	+ 3.27
$4FeS_2+22O+3H_2O=2Fe_2O_3.3H_2O+8SO_2$	Pyrite	Limonite	+ 2.93
$FeS_2+6O=FeSO_4+SO_2$ or $FeS_2+3O+H_2O=FeSO_4+H_2S$; $4FeSO_4+2O+7H_2O=2Fe_2O_3.3H_2O+4H_2SO_4$	do	do	.....
$3FeS_2+16O=Fe_3O_4+6SO_2$	do	Magnetite	−37.48
$3FeS_2+4H_2O+4O=Fe_3O_4+4H_2S+2SO_2$	do	do	−37.48
(Not formulated)	do	Hematite	.....
$4Mg_3Al_2Si_3O_{12}+15H_2O+3CO_2=3H_2Mg_3Si_4O_{12}+3MgCO_3+8Al(OH)_3$	Pyrope	Talc, magnesite gibbsite	+75.91
$4Mg_3Al_2Si_3O_{12}+6H_2O=3H_2Mg_3Si_4O_{12}+3MgAl_2O_4+2Al(OH)_3$	do	Talc, spinel, gibbsite	+36.84
$Mg_3Al_2Si_3O_{12}+5H_2O=H_4Mg_3Si_2O_9+2Al(OH)_3+SiO_2$	do	Serpentine, gibbsite, quartz	+81.61
$Mg_3Al_2Si_3O_{12}+2H_2O+CO_2=H_4Mg_2Al_2SiO_9+MgCO_3+2SiO_2$	do	Amesite, magnesite, quartz	+62.26
$3Mg_3Al_2Si_3O_{12}+8H_2O=H_{16}Mg_9Al_6Si_5O_{36}+4SiO_2$	do	Chlorite, quartz	+56.02
$Mg_3Al_2Si_3O_{12}=2MgSiO_3+MgAl_2O_4+SiO_2$	do	Enstatite, spinel, quartz	+13.51
$4Fe_3Al_2Si_3O_{12}.2Mg_3Al_2Si_3O_{12}+15H_2O=3H_{10}Fe_4Mg_2Al_4Si_4O_{25}+6SiO_2$	Pyrope, almandite	Aphrosiderite, quartz	+50.98
$Fe_3Al_2Si_3O_{12}.2Mg_3Al_2Si_3O_{12}=3MgFeSi_2O_6+3MgAl_2O_4+3SiO_2$	do	Hypersthene, spinel, quartz	+12.66
$3[2Mg_3Al_2Si_3O_{12}.Fe_3Al_2Si_3O_{12}.Ca_3Fe_2Si_3O_{12}]+4CO_2=5CaMg_2FeSi_4O_{12}.2[(Mg_4Fe_2)(Al_2Fe_3)Si_6O_{36}]+4CaCO_3+4SiO_2$	Pyrope, almandite, melanite	Hornblende, calcite, quartz	+24.55
$Ca_3Al_2Si_3O_{12}.Mg_3Al_2Si_3O_{12}.Ca_3Fe_2Si_3O_{12}+H_2O+5CO_2=2HCa_2Al_2FeSi_3O_{13}+2CaCO_3+3MgCO_3+3SiO_2$	Pyrope, grossularite, melanite	Epidote, calcite, magnesite, quartz	+39.53
$Fe_{11}S_{12}+10H_2S=11FeS_2+10H_2$	Pyrrhotite	Pyrite	+21.13
$3Fe_{11}S_{12}+116O=11Fe_3O_4+36SO_2$ or $3Fe_{11}S_{12}+36H_2O+8O=11Fe_3O_4+36H_2S$	do	Magnetite	−24.27
$4Fe_{11}S_{12}+33H_2O+162O=11(2Fe_2O_3.3H_2O)+48SO$	do	Limonite	+24.68

TABLE C.—*Chemical reactions and volume changes*—Continued.

Chemical reactions.	Source.	Products.	Volume change.
			Per cent.
$Fe_{11}S_{12}+46O=11FeSO_4+SO_2$ or $Fe_{11}S_{12}+H_2O+43O=11FeSO_4+H_2S$ $4FeSO_4+2O+7H_2O=2Fe_2O_3.3H_2O+4H_2SO_4$	Pyrrhotite	Limonite	
(Not formulated)	Quartz	(Not recorded)	
(Not formulated)	Riebeckite	(Not recorded)	
$TiO_2+Fe_3O_4=FeTiO_3+Fe_2O_3$	Rutile, magnetite	Ilmenite, hematite	−1.88
$TiO_2+FeCO_3=FeTiO_3+CO_2$	Rutile, siderite	Ilmenite	−34.77
$TiO_2+CaCO_3+SiO_2=CaTiSiO_5+CO_2$	Rutile, calcite, quartz	Titanite	−28.17
$3Ca_4Mg_3FeSi_8O_{24}+12CO_2+8H_2O=H_{16}Mg_9Fe_3Si_8O_{36}+16SiO_2+12CaCO_3$	Sahlite	Bastite, quartz	+1.93
		Bastite, quartz, calcite	+56.41
$2Ca_2MgFeSi_4O_{12}+FeCO_3+MgCO_3=Ca_2Mg_3Fe_2Si_8O_{24}+2CaCO_3$	do	Actinolite	+7.28
	Sahlite, siderite, magnesite	Actinolite, calcite	+10.81
$9CaMgFeSi_2O_6+9CO_2+8H_2O+2O=H_{16}Mg_9Fe_2Si_8O_{36}+2Fe_2O_4+9CaCO_3+19SiO_2$	Sahlite	Serpentine, magnetite, calcite, quartz.	+37.50
$3CaMgFeSi_2O_6+3CO_2+H_2O+O=H_2Mg_3Si_4O_{12}+3CaCO_3+Fe_2O_4+5SiO_2$	do	Talc, calcite, magnetite, quartz	+27.88
(Not formulated)	do	Chlorite, Epidote: One or both	
$H_2CaAl_2Si_3O_{11}2H_2O+CaCO_3=H_2Ca_2Al_2Si_3O_{13}+2H_2O+CO_2$	Scolecite	Prehnite	−16.66
$H_4Mg_3Si_2O_9+CO_2=MgCO_3+2Mg(OH)_2+2SiO_2$	Serpentine	Magnesite, brucite, quartz	+13.02
$H_4Mg_3Si_2O_9+H_2O=3Mg(OH)_2+2SiO_2$	do	Brucite, quartz	+9.82
$H_4Mg_3Si_2O_9+3CO_2=3MgCO_3+2SiO_2+2H_2O$	do	Magnesite, quartz	+18.84
(Not formulated)	do	Opal, Hematite, Limonite: One or more	
$3(H_4R_3Si_2O_9)-RO+12aq.=2(H_6R_4Si_3O_{18}+6aq.)$	do	Webskyite	
$4FeCO_3+2O+3H_2O=2Fe_2O_3.3H_2O+4CO_2$	Siderite	Limonite	−18.22
$2FeCO_3+O=Fe_2O_3+2CO_2$	do	Hematite	−49.11

TABLE C.—*Chemical reactions and volume changes*—Continued.

Chemical reactions.	Source.	Products.	Volume change.
			Per cent.
$3FeCO_3+O=Fe_3O_4+3CO_2$	Siderite	Magnetite	− 50.32
$2FeCO_3+FeS_2+2H_2O=Fe_3O_4+2H_2S+2CO_2$	Siderite, pyrite	do	− 46.67
	Siderite, marcasite	do	− 47.14
$FeCO_3+SiO_2+nH_2O=FeSiO_3+CO_2+nH_2O$	Siderite, quartz	Grünerite	− 32.53
$4Al_2SiO_5+3MgCO_3+13H_2O=H_2Mg_3Si_4O_{12}+8Al(OH)_3+3CO_2$	Sillimanite	Talc (steatite)	− 31.20
		Talc, gibbsite	+101.09
$2Al_2SiO_5+5H_2O=H_4Al_2Si_2O_9+2Al(OH)_3$	do	Kaolin	− 1.47
		Kaolin, gibbsite	+ 64.67
$6Al_2SiO_5+K_2CO_3+11H_2O=2H_2KAl_3Si_3O_{12}+6Al(OH)_3+CO_2$	do	Muscovite (damourite)	− 7.98
		Muscovite (damourite), gibbsite	+ 58.16
$2(NaCl.3NaAlSiO_4)+4H_2O+CO_2=2HNa_2Al_3Si_3O_{12}3H_2O+2NaCl+Na_2CO_3$	Sodalite	Hydronephelite	− 7.25
$2(NaCl.3NaAlSiO_4)+7H_2O+CO_2=2Na_2Al_2H_4Si_3O_{12}+2Al(OH)_3+2NaCl+Na_2CO_3$	do	Natrolite, gibbsite	− 6.52
$2(NaCl.3NaAlSiO_4)+5H_2O+CO_2=2Na_2Al_2H_4Si_3O_{12}+2AlO(OH)+2NaCl+Na_2CO_3$	do	Natrolite, diaspore	− 13.62
$2(NaCl.3NaAlSiO_4)+7H_2O+3CaCO_3=Ca_3Al_6Si_6O_{24}7H_2O+2NaCl+3Na_2CO_3$	do	Thomsonite	− 6.41
$4(NaCl.3NaAlSiO_4)+9H_2O+3CO_2=3(Na_2Al_2Si_4O_{12}2H_2O)+6AlO(OH)+4NaCl+3Na_2CO_3$	do	Analcite, diaspore	− 20.77
$4(NaCl.3NaAlSiO_4)+15H_2O+3CO_2=3(Na_2Al_2Si_4O_{12}2H_2O)+6Al(OH)_3+4NaCl+3Na_2CO_3$	do	Analcite, gibbsite	− 10.11
$2(4NaCl.K_2Na_2Al_{12}Si_{12}O_{48})+12H_2O+9CO_2=6KH_2Al_3Si_3O_{12}+3H_4Al_2Si_2O_9+8NaCl+9Na_2CO_3$	do	Muscovite, kaolin	− 37.07
(Not formulated)	Spessartite	(Not recorded)	
(Not formulated)	Spinel	Talc, Serpentine, Mica — One or more	
$4LiAlSi_2O_6+Na_2CO_3=2LiNaAl_2Si_4O_{12}+Li_2CO_3$	Spodumene	Beta-spodumene	+ 24.72
$LiNaAl_2Si_4O_{12}=LiAlSiO_4+NaAlSi_3O_8$	Spodumene (beta-spodumene)	Eucryphtite, albite	+ 0.05
$6LiNaAl_2Si_4O_{12}+K_2CO_3+2H_2O+2CO_2=2H_2KAl_3Si_3O_{12}+6NaAlSi_3O_8+3Li_2CO_3$	do	Muscovite, albite	− 0.76
$12LiAlSi_2O_6+4K_2CO_3+2CO_2+2H_2O=2H_2KAl_3Si_3O_{12}+6KAlSi_3O_8+6Li_2CO_3$	Spodumene	Muscovite, microcline	+ 31.74
(Not formulated)	do	Killinite	

TABLE C.—*Chemical reactions and volume changes*—Continued.

Chemical reactions.	Source.	Products.	Volume change.
			Per cent.
$2HFeAl_5Si_2O_{13}+3MgCO_3+15H_2O+O=H_2Mg_3Si_4O_{12}+Fe_2O_3+10Al(OH)_3+3CO_2$	Staurolite	Talc	− 44.02
		Talc, gibbsite	+ 90.96
$2HFeAl_5Si_2O_{13}+10H_2O+6MgCO_3=2H_3Mg_3FeAl_4Si_2O_{13}+2Al(OH)_3+6CO_2$	do	Chlorite (amesite), gibbsite	+103.58
$3HFeAl_5Si_2O_3+K_2CO_3+14H_2O+O=2H_2KAl_3Si_6O_{12}+Fe_3O_4+9Al(OH)_3+CO_2$	do	Muscovite (damourite)	− 24.96
		Muscovite, magnetite, gibbsite	+ 68.08
$Ca_3Al_6Si_{18}O_{48}.18H_2O+3Na_2CO_3=6NaAlSi_3O_8+3CaCO_3+18H_2O$	Stilbite	Albite	− 31.67
$Ca_3Al_6Si_{18}O_{48}.18H_2O+3K_2CO_3=6KAlSi_3O_8+3CaCO_3+18H_2O$	do	Orthoclase	− 25.66
(Not formulated)	Talc	(Not recorded)	.....
$CaTiSiO_5+CO_2=TiO_2+CaCO_3+SiO_2$	Titanite	Rutile, calcite, quartz	+ 39.22
		Octahedrite, calcite, quartz	+ 42.07
$CaTiSiO_5=CaTiO_3+SiO_2$	do	Perovskite, quartz	+ 0.14
(Not formulated)	Topaz	Talc (steatite), Muscovite (damourite), Kaolin — One or more	.....
$4NaH_5Mg_4Al_5B_3Si_6O_{31}+4K_2CO_3+Na_2CO_3=8HKMg_2Al_2Si_3O_{12}+3Na_2B_4O_7+4Al(OH)_3+5CO_2$	Tourmaline	Biotite	− 6.75
		Biotite, gibbsite	+ 3.96
(Not formulated)	do	Chlorite, Steatite — One or both	.....
$CaMg_3Si_4O_{12}+H_2O+CO_2=H_2Mg_3Si_4O_{12}+CaCO_3$	Tremolite	Talc	− 0.83
		Talc, calcite	+ 25.61
(Recrystallization)	Tridymite	Quartz	− 14.24
(Not formulated)	Uvarovite	(Not recorded)	.....
(Not formulated)	Vesuvianite	Garnet, Mica, Chlorite — One or more	.....

TABLE C.—*Chemical reactions and volume changes*—Continued.

Chemical reactions.	Source.	Products.	Volume change.
			Per cent.
(Not formulated)	Wernerite	Kaolin, Talc, Muscovite, Epidote, Biotite (One or more)	.....
(Not formulated)	Wollastonite	(Not recorded)	.....
$3ZrSiO_4+H_2O=H_2Zr_3Si_3O_{13}$	Zircon	Malacon (hydrous zircon)	+24.05
$Ca_2(AlOH)Al_2(SiO_4)_3+2CO_2+3H_2O=2CaCO_3+Al(OH)_3+H_4Al_2Si_2O_9+SiO_2$	Zoisite	Calcite, gibbsite, kaolin, quartz	+66.22
(Not formulated)	do	Mica, Amphibole, Pyroxene (Probable.)	.....

TABLE D.—*Classification of alterations, with volume changes.*

INDEX TO CLASSIFICATION.

	Page.
Carbonation	396
Carbonation and defluoridation	396
Carbonation and dehydration	396
Carbonation, dehydration, and desulphation	396
Carbonation, dehydration, and desilication	396
Carbonation and deoxidation	396
Carbonation, deoxidation, and dehydration	396
Carbonation and desilication	396
Carbonation and hydration	397
Carbonation, hydration, and dechloridation	398
Carbonation, hydration, and desilication	398
Carbonation, hydration, and desulphation	399
Carbonation, hydration, oxidation, and desilication	399
Carbonation, hydration, and silication	399
Carbonation, oxidation, dehydration, and desilication	399
Change of symmetry and molecular change	399
Chloridation	400
Deboration and decarbonation	400
Decarbonation	400
Decarbonation and titanation	400
Dehydration	400
Dehydration and decarbonation	401
Deoxidation	401
Desilication	401
Hydration	402
Hydration and decarbonation	402
Hydration and dechloridation	403
Hydration, dechloridation, carbonation, and desilication	403
Hydration, dechloridation, and decarbonation	403
Hydration and defluoridation	403
Hydration and desilication	404
Hydration, desilication, and decarbonation	401
Hydration and oxidation	404
Hydration, oxidation, and desilication	405
Hydration and silication	405
Molecular division	405
Oxidation	405
Oxidation and decarbonation	405
Oxidation, decarbonation, and desulphidation	406
Oxidation and desulphidation	406
Oxidation, hydration, and decarbonation	406
Oxidation, hydration, and desulphidation	406
Oxidation and titanation	405
Silication	406
Silication and decarbonation	407
Silication and dehydration	407
Silication, dehydration, and decarbonation	407
Silication, hydration, and decarbonation	408
Silication, oxidation, and decarbonation	408
Substitution of bases	408
Sulphidation	408
Sulphidation, deoxidation, and carbonation	408

TABLE D.—*Classification of alterations, with volume changes*—Continued.

CARBONATION.

Source.	Products.	Volume change.
		Per cent.
Brucite	Hydromagnesite	+ 73.08

CARBONATION AND DEFLUORIDATION.

Fluorite	Calcite	+ 47.66

CARBONATION AND DEHYDRATION.

Biotite	Hypersthene, sillimanite	— 24.68
Laumontite	Albite	— 34.92

CARBONATION, DEHYDRATION, AND DESULPHATION.

Gypsum	Calcite	— 50.29

CARBONATION, DEHYDRATION, AND DESILICATION.

Biotite	Epidote, spinel, quartz	— 14.71
Biotite, hematite	....do	— 18.15
Serpentine	Magnesite, quartz	+ 18.84

CARBONATION AND DEOXIDATION.

Magnetite	Siderite	+101.30

CARBONATION, DEOXIDATION, AND DEHYDRATION.

Limonite	Siderite	+ 22.27

CARBONATION AND DESILICATION.

Almandite, melanite, and pyrope	Hornblende, calcite, quartz	+ 24.55
Grossularite	Meionite, calcite, quartz	+ 54.62
Melanite (*see* Almandite).		
Pyrope (*see* Almandite).		
Serpentine	Magnesite, brucite, quartz	+ 13.02
Titanite	Octahedrite, calcite, quartz	+ 42.07
Do	Rutile, calcite, quartz	+ 39.22

TABLE D.—*Classification of alterations, with volume changes*—Continued.

CARBONATION AND HYDRATION.

Source.	Products.	Volume change.
		Per cent.
Albite, anorthite	Epistilbite, gibbsite	+37.14
Do	Heulandite, gibbsite	+37.14
Do	Stilbite, gibbsite	+43.50
Albite, anorthite, leucite	Phillipsite	+31.98
Albite, anorthite, leucite	Phillipsite, gibbsite	+40.61
Anorthite	Laumontite, gibbsite	+33.65
Do	Scolecite, gibbsite	+35.23
Augite	Biotite	+17.26
Beta-spodumene	Muscovite, albite	— .76
Biotite	Biotite-chlorite	+22.92
Do	Hydrobiotite	+ 3.80
Do	Serpentine, gibbsite, kaolin	+14.26
Enstatite	Talc	+ 9.93
Leucite	Orthoclase	—38.57
Do	Orthoclase, kaolin	—10.58
Do	Orthoclase, muscovite	—12.43
Leucite, albite, anorthite (see Albite).		
Meionite	Kaolin, calcite	+35.40
Do	Muscovite, calcite	+29.42
Nephelite	Analcite, diaspore	+ 5.49
Do	Analcite, gibbsite	+19.68
Do	Hydronephelite	+23.49
Do	Muscovite	—38.46
Do	Muscovite, kaolin	—16.50
Do	Natrolite, diaspore	+15.00
Do	Natrolite, gibbsite	+24.46
Do	Pinite, kaolin	—13.00
Phlogopite	Hydrophlogopite	+26.89
Do	Talc, diaspore	—18.27
Do	Talc, gibbsite	— 7.79
Do	Talc, gibbsite, serpentine	+ 5.23
Pyrope	Talc, magnesite, gibbsite	+75.91
Spodumene	Muscovite, microcline	+31.74
Tremolite	Talc	— .83
Do	Talc, calcite	+25.61

TABLE D.—*Classification of alterations, with volume changes*—Continued.

CARBONATION, HYDRATION, AND DECHLORIDATION.

Source.	Products.	Volume change.
		Per cent.
Sodalite	Analcite, diaspore	−20.77
Do	Analcite, gibbsite	−10.11
Do	Hydronephelite	− 7.25
Do	Muscovite, kaolin	−37.07
Do	Natrolite, diaspore	−13.62
Do	Natrolite, gibbsite	− 6.52

CARBONATION, HYDRATION, AND DESILICATION.

Actinolite	Bastite	−18.06
Do	Bastite, calcite, quartz	+38.67
Albite	Gibbsite, quartz	+ 1.58
Do	Kaolin, quartz	− 4.89
Albite, anorthite	Chabazite, gibbsite, quartz	+46.76
Do	Mesolite, gibbsite, quartz	+24.96
Do	Mesolite, gibbsite, quartz, calcite	+30.19
Anorthoclase	Gibbsite	−68.02
Do	Gibbsite, quartz	− 3.30
Do	Kaolin	−52.19
Do	Kaolin, quartz	− 9.56
Biotite, hematite	Epidote, quartz, diaspore	−18.45
Diopside	Serpentine, quartz	+ .44
Do	Serpentine, quartz, calcite	+56.32
Do	Talc	−30.13
Do	Talc, calcite, quartz	+48.74
Epidote	Calcite, gibbsite, kaolin, limonite, quartz	+69.08
Grossularite	Zoisite, calcite, quartz	+40.49
Grossularite, melanite	Epidote, calcite, quartz	+40.88
Grossularite, melanite, pyrope	Epidote, calcite, quartz, magnesite	+39.53
Hornblende	Chlorite, epidote, calcite, siderite, quartz, hematite.	+25.39
Melanite (see Grossularite).		
Orthoclase or microcline	Gibbsite, quartz	− 6.61
Do	Kaolin	−54.44
Do	Kaolin, quartz	−12.57
Do	Muscovite, quartz	−15.58

TABLE D.—*Classification of alterations, with volume changes*—Continued.

CARBONATION, HYDRATION, AND DESILICATION—Continued.

Source.	Products.	Volume change.
		Per cent.
Pyrope	Amesite, magnesite, quartz	+62.26
Pyrope (see Grossularite).		
Sahlite	Bastite, quartz	+ 1.93
Do	Bastite, quartz, calcite	+56.41
Zoisite	Calcite, gibbsite, kaolin, quartz	+66.22

CARBONATION, HYDRATION, AND DESULPHATION.

Haüynite	Chabazite, gibbsite	− 7.46
Do	Natrolite, gibbsite, calcite	+ 4.99
Do	Stilbite, gibbsite, calcite	+ .46
Noselite	Natrolite, gibbsite	−16.44

CARBONATION, HYDRATION, OXIDATION, AND DESILICATION.

Actinolite	Talc	−36.51
Do	Talc, calcite, hematite, quartz	+20.33
Augite	Chlorite, epidote, quartz, hematite	+ 8.58
Do	Chlorite, epidote, quartz, hematite, magnesite	+15.43
Olivine	Serpentine, magnetite, magnesite, quartz	+37.13
Sahlite	Serpentine, magnetite, calcite, quartz	+37.50
Do	Talc, magnetite, calcite, quartz	+27.88

CARBONATION, HYDRATION, AND SILICATION.

Hornblende, quartz	Biotite, calcite	+41.13

CARBONATION, OXIDATION, DEHYDRATION, AND DESILICATION.

Biotite	Epidote, quartz	−14.86

CHANGE OF SYMMETRY AND MOLECULAR CHANGE.

Andalusite	Cyanite	−12.03
Aragonite	Calcite	+ 8.35
Bronzite or hypersthene	Anthophyllite	[a] + 8.70
Marcasite	Pyrite	− 2.98

[a] Sp. gr. hypersthene.

TABLE D.—*Classification of alterations, with volume changes*—Continued.

CHLORIDATION.

Source.	Products.	Volume change.
		Per cent.
Albite	Marialite	+10.29
Albite, halite	do	+ 1.84
Nephelite	Sodalite	+33.14
Nephelite, halite	do	+15.64

DEBORATION AND DECARBONATION.

Tourmaline	Biotite	− 6.75
Do	Biotite, gibbsite	+ 3.96

DECARBONATION.

Anorthite, calcite	Meionite	− 3.78
Corundum, magnesite	Spinel	−29.17

DECARBONATION AND TITANATION.

Rutile, siderite	Ilmenite	−34.77

DEHYDRATION.

Albite, gibbsite	Paragonite	−18.85
Anorthoclase, gibbsite	Muscovite, paragonite	−20.04
Diaspore	Corundum	−28.18
Gibbsite	do	−61.81
Do	Diaspore	−46.82
Gypsum	Anhydrite	−37.62
Heulandite	Albite	−25.03
Do	Orthoclase	−18.44
Laumontite	Analcite	− 4.30
Limonite	Hematite	−37.78
Opal	Chert, chalcedony	
Do	Quartz	−22.81
Orthoclase or microcline, gibbsite	Muscovite (damourite)	−20.81
Stilbite	Albite	−31.67
Do	Orthoclase	−25.66

TABLE D.—*Classification of alterations, with volume changes*—Continued.

DEHYDRATION AND DECARBONATION.

Source.	Products.	Volume change.
		Per cent.
Analcite	Orthoclase, prehnite	−14.09
Anorthoclase, gibbsite	Biotite, paragonite	−10.91
Apophyllite	Pectolite	−19.48
Chabazite	Natrolite	− 4.58
Diaspore, magnesite	Spinel	−40.39
Gibbsite, magnesite	do	−60.12
Laumontite	Orthoclase, prehnite	−17.75
Mesolite	Prehnite	−15.05
Natrolite	do	−16.12
Orthoclase or microcline, magnesite, siderite, gibbsite.	Biotite	−22.33
Scolecite	Prehnite	−16.66

HYDRATION, DESILICATION, AND DECARBONATION.

Anorthoclase, calcite, hematite	Epidote, quartz	−28.30
Biotite, hematite	Biotite-chlorite, epidote, quartz, diaspore	+ 1.81
Orthoclase or microcline, calcite, hematite.	Epidote, quartz	−33.73
Orthoclase or microcline, magnesite, siderite.	Biotite, quartz	−22.64

DEOXIDATION.

Hematite	Magnetite	− 2.38

DESILICATION.

Almandite, pyrope	Hypersthene, spinel, quartz	+12.66
Pyrope	Enstatite, spinel, quartz	+13.51
Titanite	Perovskite, quartz	+ .14

TABLE D.—*Classification of alterations, with volume changes*—Continued.

HYDRATION.

Source.	Products.	Volume changes.
		Per cent.
Andalusite	Kaolin	− 3.15
Do	Kaolin, gibbsite	+ 61.87
Anhydrite	Gypsum	+ 60.30
Anorthite	Gismondite	+ 52.76
Do	Thomsonite	+ 34.65
Do	Zoisite, kaolin	− 7.77
Anorthite, hematite	Epidote, kaolin, gibbsite	+ 3.60
Cancrinite	Natrolite, gibbsite, calcite	+ 8.64
Corundum	Diaspore	+ 39.25
Do	Gibbsite	+161.83
Cyanite	Kaolin	+ 10.11
Do	Kaolin, gibbsite	+ 84.02
Hematite	Limonite	+ 60.72
Iolite (cordierite)	Chlorophyllite	− .86
Leucite	Analcite	+ 10.74
Meionite, hematite	Epidote, gibbsite	− 1.62
Nephelite	Thomsonite	+ 24.60
Pyrope	Talc, spinel, gibbsite	+ 36.84
Serpentine	Webskyite	
Sillimanite	Kaolin	− 1.47
Do	Kaolin, gibbsite	+ 64.67
Zircon	Malacon (hydrous zircon)	+ 24.05

HYDRATION AND DECARBONATION.

Andalusite	Talc (steatite)	− 32.37
Do	Talc, gibbsite	+ 97.67
Do	Muscovite (damourite)	− 9.55
Do	Muscovite, gibbsite	+ 55.47
Biotite	Chlorite	+ 22.92
Cyanite	Talc (steatite)	− 23.12
Do	Talc, gibbsite	+124.71
Do	Muscovite (damourite)	+ 2.83
Do	Muscovite, gibbsite	+ 76.74
Muscovite	Serpentine	+ 16.50
Do	Serpentine, gibbsite	+ 88.44
Do	Talc	− 25.23
Do	Talc, gibbsite	+ 46.69

TABLE D.—*Classification of alterations, with volume changes*—Continued.

HYDRATION AND DECARBONATION—Continued.

Source.	Products.	Volume change.
		Per cent.
Phlogopite	Chlorite	+ 41.02
Sillimanite	Muscovite (damourite)	— 7.98
Do	Muscovite, gibbsite	+ 58.16
Do	Talc (steatite)	— 31.20
Do	Talc, gibbsite	+101.09
Staurolite	Chlorite (amesite), gibbsite	+103.58

HYDRATION AND DECHLORIDATION.

Sodalite	Thomsonite	— 6.41

HYDRATION, DECHLORIDATION, CARBONATION, AND DESILICATION.

Marialite	Muscovite, quartz	— 16.74

HYDRATION, DECHLORIDATION, AND DECARBONATION.

Marialite	Kaolin, talc	+ 7.69

HYDRATION AND DEFLUORIDATION.

Chondrodite	Serpentine, brucite	+ 30.15
Clinohumite	do	+ 38.39
Humite	do	+ 35.53

TABLE D.—*Classification of alterations, with volume changes*—Continued.

HYDRATION AND DESILICATION.

Source.	Products.	Volume change.
		Per cent.
Albite	Analcite, quartz	+20.82
Do	Natrolite, quartz	+19.95
Albite, anorthite, orthoclase	Albite, zoisite, muscovite, quartz	.....
Almandite, pyrope	Aphrosiderite, quartz	+50.98
Anorthite	Zoisite, gibbsite, quartz	— 4.58
Do	Prehnite, gibbsite, quartz	+14.85
Anorthite, hematite	Epidote, gibbsite, quartz	+ 6.57
Anthophyllite	Bastite	+12.09
Do	Bastite, quartz	+34.09
Bronzite or hypersthene	Bastite	[a] +22.77
		[b] +15.65
Do	Bastite, quartz	[a] +46.87
Cummingtonite	Bastite	+14.20
Do	Bastite, quartz	+36.76
Enstatite	Serpentine	+14.25
Do	Serpentine, quartz	+38.36
Orthoclase (*see* Albite).		
Prehnite	Chlorite, quartz	+ 3.27
Pyrope	do	+56.02
Do	Serpentine, gibbsite, quartz	+81.61
Pyrope (*see* Almandite).		
Serpentine	Brucite, quartz	+ 9.82

HYDRATION AND OXIDATION.

Anthophyllite	Talc, hematite	+11.41
Do	Talc, limonite	.....
Bronzite or hypersthene	Talc, hematite	.....
Do	Talc, limonite	.....
Do	Talc, magnetite	[b] +14.68
		[a] +21.73
		[c] +18.20
Magnetite	Limonite	+64.63
Olivine	Serpentine, magnetite	+29.96

[a] Sp. gr. hyperstbene. [b] Sp. gr. bronzite. [c] Average sp. gr. bronzite and hypersthene.

TABLE D.—*Classification of alterations, with volume changes*—Continued.

HYDRATION, OXIDATION, AND DESILICATION.

Source.	Products.	Volume change.
		Per cent.
Bronzite or hypersthene	Serpentine, hematite	[a] — 2.21
Do	Serpentine, hematite, quartz	[a] +33.94
Hypersthene	Talc, magnetite, quartz	+12.84
Do	Serpentine, magnetite, quartz	+20.24
Olivine	do	+12.43
Do	do	+15.19

HYDRATION AND SILICATION.

Hornblende, quartz	Biotite, epidote	—30.05

MOLECULAR DIVISION.

Spodumene (beta-spodumene)	Eucryptite, albite	+ .05

OXIDATION.

Ilmenite	Octahedrite, hematite	+12.20
Do	Octahedrite, magnetite	+11.07
Do	Rutile, hematite	+ 7.16
Do	Rutile, magnetite	+ 6.02
Magnetite	Hematite	+ 2.44

OXIDATION AND TITANATION.

Rutile, magnetite	Ilmenite, hematite	— 1.88

OXIDATION AND DECARBONATION.

Ankerite	Hematite	
Do	Magnetite	
Parankerite	Hematite	
Do	Magnetite	
Siderite	Hematite	—49.11
Do	Magnetite	—50.32

[a] Sp. gr. hypersthene.

TABLE D.—*Classification of alterations, with volume changes*—Continued.

OXIDATION, DECARBONATION, AND DESULPHIDATION.

Source.	Products.	Volume change.
		Per cent.
Siderite, marcasite	Magnetite	—47.14
Siderite, pyrite	do	—46.67

OXIDATION, HYDRATION, AND DECARBONATION.

Ankerite	Limonite	
Meionite	Epidote, gibbsite	+ 7.55
Parankerite	Limonite	
Siderite	do	—18.22
Staurolite	Muscovite (damourite)	—24.96
Do	Muscovite, magnetite, gibbsite	+68.08
Do	Talc	—44.02
Do	Talc, gibbsite	+90.96

OXIDATION, HYDRATION, AND DESULPHIDATION.

Marcasite	Limonite	— 0.14
Pyrite	do	+ 2.93
Pyrrhotite	do	+24.68

OXIDATION AND DESULPHIDATION.

Marcasite	Magnetite	—39.34
Pyrite	do	—37.48
Pyrrhotite	do	—24.27

SILICATION.

Corundum, quartz	Cyanite	— 6.59
Do	Sillimanite	+ 4.38
Gehlenite	Grossularite	— 4.42
Gehlenite, quartz	do	—18.56
Olivine, quartz	Anthophyllite	— 1.48
Nephelite, quartz	Albite	— .41

TABLE D.—*Classification of alterations, with volume changes*—Continued.

SILICATION AND DECARBONATION.

Source.	Products.	Volume change.
		Per cent.
Ankerite or parankerite, quartz	Actinolite	−32.72
Do	Actinolite, calcite	−22.62
Do	Sahlite	−37.27
Bronzite or hypersthene, calcite, quartz	Actinolite	[a]−10.77 [b]− 7.40
Calcite	Wollastonite	+10.81
Calcite, quartz	do	−31.48
Dolomite	Diopside	+ 2.03
Dolomite, quartz	do	−40.11
Dolomite	Tremolite, calcite	+ 9.89
Dolomite, quartz	do	−25.20
Dolomite	Tremolite, wollastonite	+14.00
Dolomite, quartz	do	−33.09
Forsterite, calcite, quartz	Tremolite	−12.29
Olivine, calcite, quartz	Actinolite	−13.34
Rutile, calcite, quartz	Titanite	−28.17
Siderite, quartz	Grünerite	−32.53

SILICATION AND DEHYDRATION.

Analcite, quartz	Albite	−17.25
Diaspore, quartz	Cyanite	−22.61
Do	Sillimanite	−13.52
Gibbsite, quartz	Cyanite	−49.61
Do	Sillimanite	−43.68

SILICATION, DEHYDRATION, AND DECARBONATION.

Diaspore, quartz, calcite	Margarite	−14.08
Do	Zoisite	−29.44
Diaspore, quartz, K_2CO_3	Muscovite	−54.21
Gibbsite, quartz, calcite	Margarite	−38.92
Do	Zoisite	−43.06
Gibbsite, quartz, K_2CO_3	Muscovite	−64.99

[a] Sp. gr. bronzite. [b] Sp. gr. hypersthene.

TABLE D.—*Classification of alterations, with volume changes*—Continued.

SILICATION, HYDRATION, AND DECARBONATION.

Source.	Products.	Volume change.
		Per cent.
Corundum	Margarite	+159.02
Corundum, quartz, calcite	do	− 1.22
Corundum	Zoisite	+261.34
Corundum, quartz, calcite	do	− 23.58
Corundum	Muscovite (damourite)	+264.25
Corundum, quartz, K_2CO_3	do	+ 1.62

SILICATION, OXIDATION, AND DECARBONATION.

Ilmenite	Titanite	+ 76.35
Ilmenite, calcite, quartz	Titanite, magnetite	− 22.35

SUBSTITUTION OF BASES.

Augite	Hornblende	+ 4.30
Augite, siderite, magnesite	Hornblende, calcite	+ 6.14
Calcite	Dolomite	− 12.30
Diopside	Tremolite	+ 5.68
Diopside, magnesite	Tremolite, calcite	+ 10.55
Hornblende	Augite	− 4.13
Leucite	Orthoclase, nephelite	− 7.59
Muscovite	Paragonite	− 2.67
Olivine, anorthite	Actinolite, spinel	− 7.18
Sahlite	Actinolite	+ 7.28
Sahlite, siderite, magnesite	Actinolite, calcite	+ 10.81
Spodumene	Beta-spodumene	+ 24.72

SULPHIDATION.

Pyrrhotite	Pyrite	+ 21.13

SULPHIDATION, DEOXIDATION, AND CARBONATION.

Hematite	Marcasite, siderite	+ 78.73
Do	Pyrite, siderite	+ 76.12

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